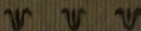


FIRST BOOKS OF SCIENCE



APPLIED ELECTRICITY

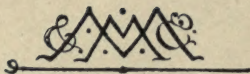


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A FIRST BOOK OF APPLIED ELECTRICITY

BY

S. R. ROGET

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PREFACE

IN this presentation of a few of the elementary principles that underlie the useful applications of electricity and magnetism, reference has been made to the manifestations of electricity which are most often met with in daily life, without first requiring the reader to survey aspects of the subject which, although of ultimate theoretical importance, are not the basis of the applications with which he is already acquainted. For this reason, it has been sought to make the reader familiar with electric currents and their various effects, pointing out how some of these are applied, before he is introduced to electrostatics; for it is considered more important for him to think in volts and amperes than in electrostatic units.

In a work of this size, it would have been impossible to enter into details of real electrical engineering practice without unduly restricting the outline of the principles involved.

Only the most elementary mathematics are employed, and the object has been more to help to give an understanding of principles than to provide the equipment for the exact calculations which will be of more profit at a later stage when those principles have been mastered.

A few numerical examples and exercises are given, but these are intended more as types than as a complete

course. In the same way, the experiments suggested at the end are all of the most elementary nature, requiring only the simplest appliances. Teachers and students having a wider range of apparatus at their disposal will be able to extend the experimental illustration of the subject beyond the limits possible of inclusion in a work of this size.

It should be added that the book is entirely independent of the requirements of examinations, and is addressed as much to students who may later take up the practice of electrical engineering as to the general reader anxious to understand a little of these matters.

The Author desires gratefully to acknowledge the kind help of Sir Richard Gregory and Mr. A. T. Simmons during the preparation of the work.

S. R. R.

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CHAPTER I.

ELECTRIC CURRENTS AND CIRCUITS.

Flow of Current.—An electric **current** may be said to flow along a wire in much the same way that water flows along a pipe, but it is not so easy to describe what it is that passes along. We know what effects are produced; we know how to make a current flow whenever we want it; we can measure it, and we have many practical ways of using it, but we cannot give a simple answer to the question "what is electricity?" Electricity may be thought of as something which can, so to speak, occupy the wire, and can be pushed along or can remain still according as an **electromotive force** is applied or not.

The closed Circuit.—Most of us are familiar with the fact that a current flows in the wires that lead to and from an electric lamp, bell, motor, or other piece of electrical apparatus, where it produces some effect that we can see or hear, whether the current comes from a small pocket battery, or through the mains from a great electric light station, and that the current can be made to flow or not as required by a switch or bell-push; but the idea must be grasped that it is only when the **circuit** of wires, or other material that can conduct electricity, is complete that a current can flow. Whatever is the source of the electromotive force (which we shall generally refer to as **E.M.F.**) it is necessary to have a conducting path from one end, or **pole**, through the external circuit, to the other pole, so that the current can, as it were, chase itself round and round.

The way in which the current goes out of the battery **B** through the switch **S** and the lamp **L** and returns to the

battery when the switch is closed and not when it is open, is made clear in Figs. 1 and 2. It is usual to speak of the two poles of the battery as the **positive** (+) and **negative** (-) poles, and to think of the current starting from the positive and returning to the negative pole. The points to which the lead and return wires are attached are called **terminals**.

We will defer, for the moment, consideration of how it comes about that a battery produces a current, and why the current lights the lamp. The battery should, at present, be regarded as a handy source of E.M.F., ever ready to make a current flow when a closed circuit is provided.

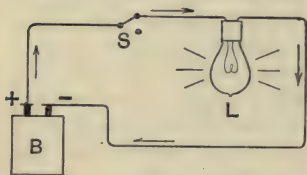


FIG. 1.—Circuit closed, lamp alight.

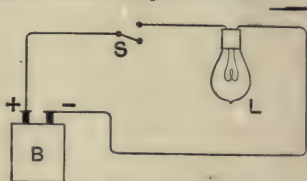


FIG. 2.—Circuit open, lamp extinguished.

It should be pointed out that the case is rather different from that of water flowing in a pipe out of a tank, as no return is required for the water. It is more like that of a hot-water heating system in which water circulates through the radiators and goes back to the boiler to be heated again.

Conductors and Insulators.—As a conducting path is required for the current, the question at once arises as to what materials can be employed for this path. Materials can, in this respect, be roughly divided into two classes: **Conductors**, which allow electric currents to flow through them, and **Insulators** (or non-conductors), which do not.

All metals, and certain other substances, among which is carbon,¹ are good conductors. Copper, among those

¹ A familiar form of carbon of conducting power is pencil "lead" or graphite; coke conducts also to a less degree, and a special form of carbon is prepared in rods, etc., for electrical purposes.

in common use, is the best; hence wires for electric lighting circuits are generally made of that metal. Some liquids, such as salt water, are also good conductors. Insulators include a large class of materials, among which may be mentioned india-rubber, glass, china, wax, mica, varnish, dry paper, and silk. Indeed, with the exception of metals and liquids not of an oily nature, most everyday substances are fairly good insulators.

As will be seen later, the difference between conductors and insulators is really one of degree. The very best insulator allows an infinitesimal current to pass and the conducting power even of metals varies considerably. For present purposes, however, an insulator may be regarded as stopping the passage of a current entirely.

Resistance.—Some idea may now be obtained of how the amount of current flowing in a circuit varies according to circumstances. Consider the simple case of a constant E.M.F., such as that of a battery sending a current through a wire. If we take away the wire and replace it by a much longer one of the same material, a much smaller current will flow; this is because we have increased what is called the **resistance** of the circuit. This property of resistance to the flow of a current is measured in units called **Ohms**. The E.M.F. is measured in **Volts** and the current which results is measured in **Amperes**. These units are named after some of the pioneers of electrical science. Let us now consider how these quantities are related.

Ohm's Law.—It has been found that, for the same E.M.F., doubling the resistance of the circuit halves the current, tripling it reduces the current to one-third, and so on. On the other hand, with the same resistance, doubling the E.M.F. would double the current. We can put the relation conveniently by saying that the current is proportional to the E.M.F. divided by the resistance. Thus

$$\text{Current in amperes} = \frac{\text{E.M.F. in volts.}}{\text{Resistance in ohms}},$$

or in symbols
$$I = \frac{E}{R}.$$

The Greek letter ω (omega) is sometimes employed instead of the word ohms.

The equation $I = E/R$ is called **Ohm's law**, and by it we see that **One ampere is the result of one volt being applied to one ohm**, or, indeed, of 100 volts being applied to 100 ohms. Knowing two out of these three quantities, we can always find the third, for we can write the equation in either of the following forms :

$$I = \frac{E}{R}, \quad E = IR \quad \text{or} \quad R = \frac{E}{I}.$$

The extreme cases are an **open circuit**, which may be considered as an infinite resistance, where no current consequently passes, although the E.M.F. is, of course, there just the same, and a so-called **short circuit**, where a very small resistance (in proportion to the E.M.F.) allows a very large current to flow, so large sometimes, especially in the case of high voltages, as to produce considerable damage.

EXAMPLES.—(1) The E.M.F. of a battery is 2.5 volts, and the resistance of the circuit, including the lamp, is 3.25 ohms. What is the current flowing through the lamp?

$$\frac{E}{R} = \frac{2.5}{3.25} = 0.77 \text{ ampere.}$$

(2) We have a circuit consisting of lead and return wires each composed of 20 miles of wire, with a resistance of 8.92 ohms per mile. The rest of the apparatus in the circuit has a resistance of 20 ohms. It is desired to pass a current of 0.2 ampere. What E.M.F. will be required?

The total resistance equals $20 \times 8.92 + 20 = 198.4$ ohms. The E.M.F. required $= IR = 198.4 \times 0.2 = 39.68$ volts.

(3) A lamp on a 100 volt circuit is taking half an ampere. What is its resistance? (assuming that the resistance of other parts of the circuit is negligible).

$$R = \frac{E}{I} = \frac{100}{0.5} = 200 \text{ ohms.}$$

Electromotive Force and Potential Difference.—E.M.F. is often spoken of by engineers as “pressure” or as “voltage.” The ordinary battery of a pocket lamp has an E.M.F. of about $2\frac{1}{2}$ volts. The voltage of an electric

light circuit may be in the neighbourhood of 100 or 200 volts, and for transmission of power over long distances, pressures of thousands of volts are used.

So far, we have thought of applying an E.M.F. to a circuit as a whole, having a certain total resistance, and we have considered how much current is the result. We will now consider the conditions at various points on the circuit. Suppose that we have an E.M.F. of 10 volts in a circuit of total resistance 10 ohms. Suppose also for the sake of convenience, that the 10 volt battery which we are using has itself an

"internal" resistance of one ohm (for a battery, like the rest of the circuit, must have some resistance) and that the rest of the circuit is a uniform wire of 9 ohms resistance. We have thus a total resistance of 10 ohms; consequently a current of one ampere will flow. We can regard each one ohm section, whether it be the



FIG. 3.—Potential drop.

battery or a part of the wire, as using up one volt of the total E.M.F. Thus the actual voltage across the terminals of the wire when the current is flowing is only 9 volts, although the E.M.F. of the circuit is 10 volts, as one volt is used up in forcing the current through the battery itself. We can think of a continuous **fall of potential**, as it is called, along the wire. From this point of view, it is perhaps clearer to represent the wire as a straight line as in Fig. 4, instead of as a circle as in Fig. 3.

Now we can consider any part of the circuit separately and apply Ohm's law to it exactly as we did for the whole circuit, only our voltage will be the fall or drop of potential, or, as it is often called, the **potential difference** (or P.D.) across it and the resistance will be just the resistance of the section. Thus the drop of potential across DF, for example, will be 2 volts, its resistance 2 ohms and the

current $\frac{E}{R} = \frac{2}{2} = 1$ ampere. Again, supposing we know the resistance of part of a circuit and the current flowing in it, we can find the potential drop which $= IR$ (in this case $1 \times 2 = 2$ volts). The potential drop due to resistance is often spoken of as "**IR drop.**"¹ It is very important to keep clear the difference between the total E.M.F. and the P.D. between any two points, although in many practical cases of a battery, or other source of E.M.F. of small resistance, the P.D. at its terminals is very nearly equal to the true E.M.F. In the case of an electric lamp, say

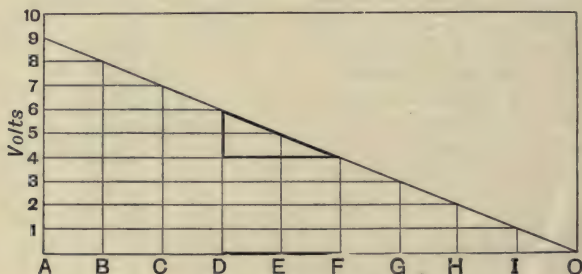


FIG. 4.—Potential drop.

on a 200 volt circuit, nearly all the potential drop is in the lamp, which is of high resistance, although there is some slight potential drop in the mains and house wiring.

EXAMPLE.—A long cable with a total resistance of 2 ohms, is to deliver a current of 25 amperes at a pressure of 500 volts at the far end. What pressure will be necessary at the generating station?

The drop of potential $= IR = 25 \times 2 = 50$ volts.

Therefore the voltage required will be $500 + 50 = 550$ volts.

Series and Parallel Connections.—If a circuit is arranged in the simple way that we have been considering, the current going in turn through all parts of it, all these portions are said to be in **Series**. Fig. 5 shows 10 lamps

¹ Or in old-fashioned books as "**CR drop,**" for C was formerly used for current before I was the universal symbol.

in series. The source of the E.M.F. is here supposed to be a dynamo. This, as will be seen later, is a machine which, when driven by an engine or other source of power, is capable of producing an E.M.F. and turning mechanical power into electrical power. With a 100 volt dynamo,

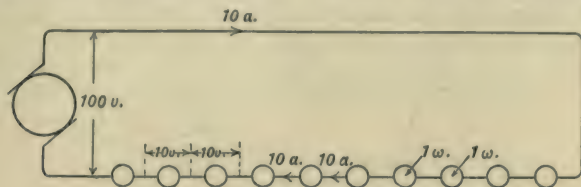


FIG. 5.—Ten lamps in series.

neglecting the drop in the dynamo and the wires, each lamp will have 10 volts across its terminals.

There is, however, another and a more usual way of arranging ten lamps on a circuit, which is called connecting them in **parallel** (Fig. 6). In this case the current divides and each lamp has the full 100 volts (neglecting drop) across its terminals. A lamp which is so constructed as to take the current necessary to light it properly, when it

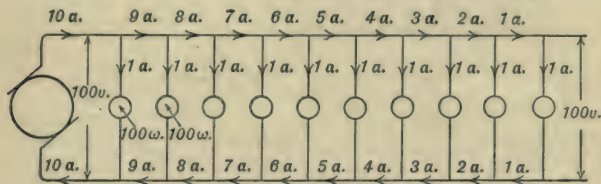


FIG. 6.—Ten lamps in parallel.

has 100 volts across its terminals, is called a 100 volt lamp. Electric light systems are so regulated as to keep the voltage across the mains constant at 100, 200 or other exact voltage, so that all we have to do is to put on a lamp of the correct voltage. The 100 volt lamps illustrated in Fig. 6 will of course have a much higher resistance than the little 10 volt lamps of Fig. 5. The practical advantage of putting lamps in parallel on a circuit is not

only that they can be turned on and off independently, but that it is easier to arrange different sized lamps on the same circuit, for if they are in series, all have to be accurately matched so that they light up with exactly the same current (amperes).

Series-parallel Combinations.—Any combination of the series and parallel connections can be used. Examples of such series-parallel arrangements with the currents, P.D.'s and resistances marked for the same total dynamo

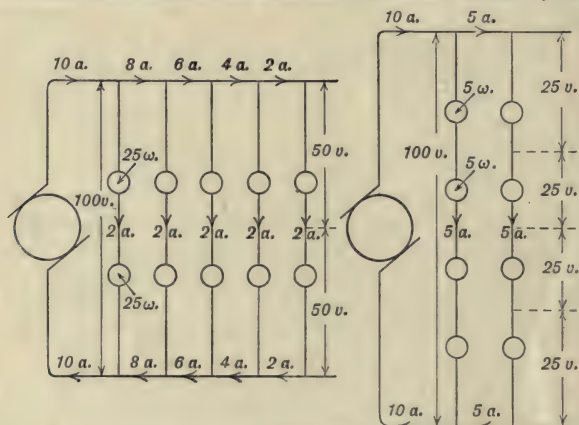


FIG. 7.—Ten lamps in series-parallel.

current as in Figs. 5 and 6, may be studied in Fig. 7. When two parts of a circuit are in parallel, one is sometimes spoken of as forming a **shunt** to the other. This is particularly the case where their resistances are very unequal.

When resistances are in series, their ohmic values are added. Thus two ten ohm resistances in series give us twenty ohms. If they are in parallel, the combined resistance is only half, that is, 5 ohms. The matter may be put into symbols more generally thus :

In series $R = R_1 + R_2 + R_3 + \dots$

In parallel $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$

Very complicated cases of unequal resistances in combined series-parallel connection give rather tedious calculations, but all can be worked out by applying the above formulae to each branch of the circuit.

EXAMPLE.—Resistances of 1, 5 and 7 ohms respectively are placed first in series and then in parallel. Their combined resistance in series = $1 + 5 + 7 = 13$ ohms. Let R = their combined resistance in parallel, then

$$\frac{1}{R} = \frac{1}{1} + \frac{1}{5} + \frac{1}{7} = \frac{35 + 7 + 5}{35} = \frac{47}{35};$$

$$\therefore R = \frac{35}{47} = 0.745 \text{ ohms.}$$

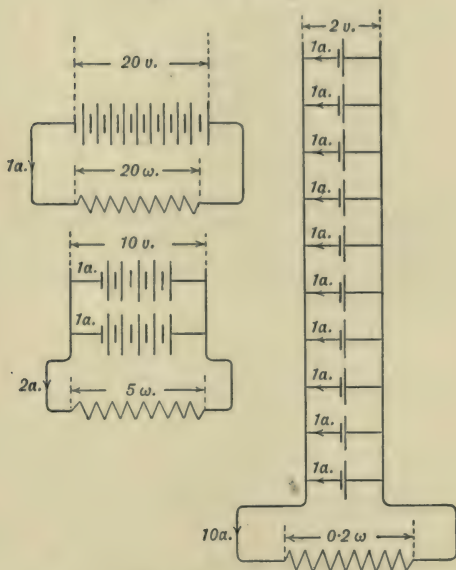


FIG. 8.—Series and parallel groupings of cells.

Sources of E.M.F. may be put in series or parallel in exactly the same way as resistances. Suppose we had ten two-volt cells; put them all in series and we have

a 20 volt battery, but put them all in parallel and we still get only 2 volts. These and other arrangements are shown in Fig. 8, where the conventional symbol of a long and a short line is used to denote each cell. The currents in each case are worked out for an external resistance of one ohm and negligible internal resistance.

Regulating Resistances.—A convenient way of arranging resistances so that a current can be regulated by cutting

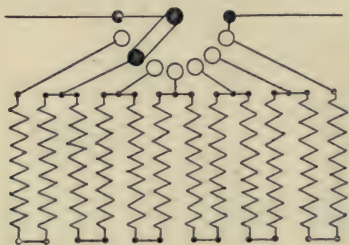


FIG. 9.—Rheostat.

resistance in or out is shown in Fig. 9, where several resistance coils are connected to a multiple contact switch. Such a device, of which many forms are used in practice, is called **rheostat**.

CHAPTER II.

RESISTANCE AND HEATING EFFECTS.

Specific Resistance.—We will now enquire a little more closely into the factors that determine the resistance of any conductor. It will readily be seen that a long thin conductor has more resistance than a short thick one of the same material. The resistance of a wire, in fact, depends upon

- (1) its cross section, to which it is inversely proportional;
- (2) its length, to which it is directly proportional, and
- (3) the **specific resistance** of the material of which it is made.

This may be explained in symbols as

$$R = \frac{l}{a} \rho,$$

where R = resistance, l = length, a = cross section (or sectional area) and ρ (Greek letter *rho*) is the specific resistance of the material.

Specific resistance may be defined as the resistance of a conductor of that material 1 cm. long and 1 sq. cm. in section. The specific resistances of a few typical materials are given on page 12.

Effect of Temperature on Resistance.—The resistance of the same piece of wire is different at different temperatures. Generally speaking, heating a wire increases its resistance and cooling it decreases its resistance. It is usual to give the specific resistance at a standard temperature and to give a **temperature coefficient**, which is the

factor by which we must multiply the original resistance at the standard temperature to obtain the increase of resistance to add on for each degree of temperature rise. Thus, the resistance at any temperature t (in degrees Centigrade) $= R_t = R_0(1 + at)$, where a (Greek letter *alpha*) is the temperature coefficient and R_0 the resistance at 0°C .

Some substances, the most notable of which is carbon, decrease in resistance when heated, that is to say, their temperature coefficient is negative. Another class of conductor, such as the "alkaline earths" (magnesia, zirconia, etc.), carries the effect of temperature to the extreme of being practically non-conducting at ordinary temperatures but are fairly good conductors when red hot, and modern theories indicate that at sufficiently high temperatures all bodies become conductors. The resistance of some materials is affected by light falling upon them. Thus the resistance of selenium, when in a crystalline state is, in sunshine, about half what it is in the dark.

The specific resistances in the table below are expressed for convenience in microhms (millionths of an ohm) per cubic centimetre.

Material.	Specific Resistance at 0°C .	Temperature coefficient.
Silver - - -	1.50	+ 0.0037
Copper (hard drawn)	1.62	0.0043
Iron (telegraph wire)	15.00	0.0070
Mercury - - -	94.07	0.0009
" German Silver " -	20.2	0.0003
" Constantan " -	49	0.0002
Carbon (arc lamp) -	7000	- 0.0005

The values in the above table only hold for the ordinary range of atmospheric temperatures. For more extreme differences of temperature the relation for some substances, particularly alloys, is more complex. Pure metals have a very steady temperature coefficient over a

large range of temperature, and electrical thermometers are often used for determining very high or very low temperatures by measuring the resistance of a platinum wire, exposed to the temperature to be determined, by methods referred to later.

EXAMPLE.—Find the resistance of an iron telegraph wire 500 yards long, 0.01 sq. in. cross section at 59° F.—

500 yards = 45.735 cm., 0.01 sq. in. = 0.0645 sq. cm., and the specific resistance of iron telegraph wire at 0° C. is 15 microhms per c.c.

The resistance at 0° C.

$$= \frac{l}{a} \rho = \frac{45.735}{0.0645} \times 15 \text{ microhms} = 10.64 \text{ ohms. } 59^\circ \text{ F.} = 15^\circ \text{ C.}$$

Resistance at 15° C. = $R_0(1 + \alpha t)$

$$= 10.64(1 + 0.007 \times 15) = 10.64 \times 1.105 = 11.75 \text{ ohms.}$$

The Heating Effect of a Current.—We have seen that resistance is something that tends to oppose the flow of current and the current may be regarded as having to make a fight to get through, that is, to expend energy in the process. This energy reappears in the form of heat, and it is important to realise that whenever a current passes through a conductor, heat is developed. Where the resistance is high, as in an incandescent lamp, and the conductor is small, the heating effect is very easily appreciated, but a certain amount of heat is also developed in large conductors of low resistance.

The amount of heat developed in one second is proportional to the square of the current multiplied by the resistance; therefore, the energy lost as heat in a wire is often referred to as the I^2R loss. This, by Ohm's law, is the same thing as EI . Thus the energy per second put into a wire and reappearing in the form of heat is proportional to the potential drop multiplied by the current. When we are thinking of the "Power" (*i.e.* energy per second) put into a circuit we generally express it in units called **watts**, which are the product of the volts and the amperes. One watt acting for one second produces an amount of heat which is sometimes called

one **joule**. One Joule is equivalent to 0.24 calories or 0.00094 British Thermal Units.¹ It will be seen later that the energy put into the circuit can reappear in other ways besides heat, for example, as mechanical work, and in this connection it is useful to remember that **one horse-power is represented electrically by 746 watts**.

In whatever form the energy reappears, this unit, the watt, is used just the same, but it is more commonly met with as the larger unit the **kilowatt**, which is 1000 watts; and the unit by which electrical energy is sold is the **Kilowatt-hour** (called by some writers the **Kelvin**) or **Board of Trade Unit**.

EXAMPLES.—(1) A current of 5 amperes flows in a coil of wire of 20 ohms resistance. The heat developed per second is $I^2R = 25 \times 20 = 500$ joules. This is equivalent to $500 \times 0.24 = 120$ calories. In one minute, therefore, 7200 cal. would be developed, which could raise the temperature of 100 c.c. of water from 18° C. to 100° C. (boiling point).

(2) If an incandescent lamp on a 100 volt circuit takes half an ampere, it will consume 50 watts. Twenty such lamps will require $20 \times 50 = 1000$ watts, that is, one kilowatt (or $\frac{1000}{746} = 1.34$ electrical horse-power), and running for six hours will consume 6 kilowatt-hours or Board of Trade units. This at 5d. per unit will cost 2s. 6d.

Although, as we have seen, we can calculate without difficulty the total heat generated in a conductor by the passage of a current, it is not such a simple matter to determine the temperature rise that will result, as this depends also on the rate at which the heat can be dissipated. It is easy to see that a short thin wire may rise to a very high temperature with a smaller expenditure of energy than is required to render a larger conductor scarcely perceptibly warm.

Uses of Electric Heating.—Examples of electric heating are found in electric incandescent lamps where the "filament" is kept at a white heat by the current, in

¹ One calorie will raise the temperature of 1 gramme of water one degree Centigrade and one B.Th.U. will raise the temperature of 1 lb. of water one degree Fahrenheit.

electric radiators for warming rooms, and in other domestic and industrial apparatus. The principle in all these applications is the same. The heat is produced just at the part of the circuit where it is required by the use of high resistance conductors of suitable dimensions. Some further notes on electric heating appear in Chapter XI.

Hot-Wire Measuring Instruments.—The heating effect of a current furnishes a means which is sometimes used for measuring its strength. Fig. 10 shows the essential parts of a hot wire instrument in which the sag of the wire AB, which expands owing to being heated by the current, allows the spring S to cause the deflection of the pointer. For measuring anything but small currents in this way, it is usual to connect such an instrument across a low resistance which forms a **shunt**, so that it is only a known fraction of the current which passes through it. This amounts to using the instrument to measure the drop of potential across the terminals of the shunt by noting the effect of the current produced in the hot wire by the drop of potential. In a similar way, a hot-wire instrument of high resistance, or in series with a high resistance, can be used to measure directly the voltage between any two points. Such an instrument is called a hot-wire **voltmeter**. As we shall see, there are other properties of currents which are more commonly used for the measurement of currents and voltages.

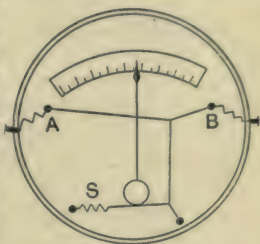


FIG. 10.—Hot-wire instrument.

CHAPTER III.

MAGNETIC EFFECTS OF THE CURRENT.

The Electro-Magnet.—A current reveals its presence in a conductor in other ways besides by producing heat. One of the most important is by its power of producing what is known as **magnetism**. If a wire is wound into a coil round a piece of soft iron, and a current is passed through it (Fig. 11), the piece of iron acquires the property

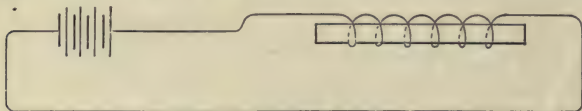


FIG. 11.—The electro-magnet.

of attracting other pieces of iron. In other words it, becomes a **magnet**, or in this case, what is called an **electro-magnet**. The magnetic effect lasts only so long as the current is passing, and to all intents and purposes ceases immediately the current is cut off.

North and South Poles.—Most people are more or less familiar with the properties of ordinary magnets or **permanent magnets** as they are called, and later we shall have more to say about these. Here magnetism may be thought of as something which is always present when an electric current flows, without going into more details about the effect it leaves behind in materials, such as hard steel. It will suffice at this stage to bear in mind the following fundamental ideas, the full meaning of which will appear more clearly later.

- (1) The two ends of a magnet are called its North and South Poles, and when a magnet is suspended freely, it takes up a position such that its North pole points approximately to the North Pole of the Earth and its South Pole to the South Pole of the Earth.
- (2) Both poles attract unmagnetised pieces of iron and the opposite poles of other magnets, and repel like poles of other magnets.

Electric Bells.—A familiar example of the action of an electro-magnet is presented by the ordinary electric bell. In the form illustrated diagrammatically in Fig. 12, the

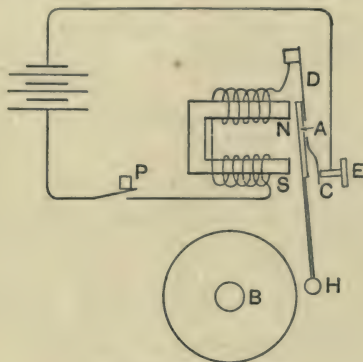


FIG. 12.—The electric bell.

electro-magnet is U-shaped with a coil on each limb, and the poles N. and S. are side by side. When the circuit is completed by the bell-push P, the current flows in the coils and the magnet thus produced attracts the **armature** or piece of soft iron A, fixed by a spring at one end D and carrying the hammer H at the other end causing it to hit the bell B. This would simply produce one "ting" on the bell (and such "single contact" bells are sometimes used). The ordinary type of household bell or **trembler bell** is fitted with the contact arrangement C. The contact spring leaves the point of the screw E as soon as the

armature has moved a little way, and interrupts the circuit. The magnet no longer attracts, and the armature flies back, re-establishing the contact; it is attracted once more, but again breaks the circuit as the bell is hit. This process is repeated over and over again until the push is released and the circuit is interrupted altogether.

The Poles of an Electro-Magnet.—Going back to the case of a long straight coil over an iron “core,” it is very important to note that the North Pole is produced at the end where the current goes round in a direction contrary to that of the hands of a clock, looking at the coil from that end, and the South Pole where it goes with the hands of the clock.

Take a good look at Fig. 13, and remember :

Counterclockwise, North,
Clockwise, South.

Of course, if the wires were so arranged that the whole coil could be suspended free to swing, it would point

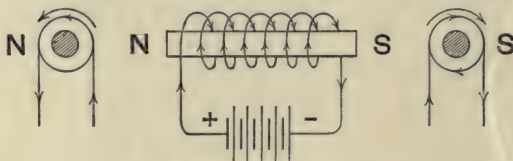


FIG. 13.—The poles of an electro-magnet.

North and South just like a compass needle. The North pole of such an electro-magnet would attract the South-seeking pole of a compass needle and repel the North-seeking pole of the compass needle, and *vice versa*.

Lines of Force.—Imagine the iron core removed but the current still on; we have then what electricians call a **solenoid**, which still has the properties of a magnet, although to a much smaller extent than when it had the iron core within it. Through the axis of the solenoid there is something passing along, so to speak, which we call **magnetic flux**, and this we think of as being composed of **lines of force**, which produce feeble magnetic effects

when just passing through air, but powerful magnetic effects when passing through iron or other magnetic material. The principal magnetic materials are iron and steel, but some other materials, including nickel and cobalt, are also capable of being made magnetic.

These lines of force form closed circuits. Although they pass through the inside of the coil and through the iron when it is there, going out at the North pole and coming in at the South pole, they must find their way

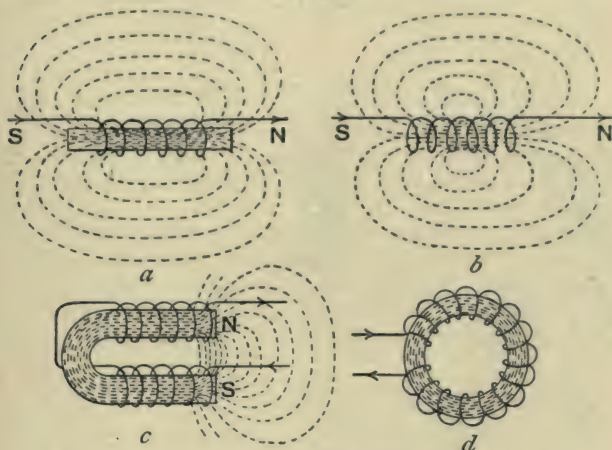


FIG. 14.—Lines of force.

back somehow; and this is done through the surrounding air in the way shown for our straight electro-magnet or empty solenoid in Fig. 14 (a), and for another form of magnet at (b) in the same Fig. The lines may return partly through other pieces of iron, or entirely through the air or other non-magnetic material. But it is important to realise that where they enter a piece of magnetic material, a North pole is produced, and where they leave it a South pole is produced. If the current-carrying wire is wound round a closed ring of iron, as at (d) in Fig. 14, the lines of force do not leave the iron at all and no poles are

produced, but the iron is of course as truly magnetised as if there were an air gap where poles are exhibited.

The space through which the lines of force pass is known as a **Magnetic field**. If a compass needle is suspended inside a solenoid, it will set itself to point along the lines



FIG. 15.—Lines of force in a solenoid.

of force as in Fig. 15, and indeed it will do so at any part of the field, so that it can be used to explore the distribution of the external field by mapping the direction of the lines of force.

Now imagine all the turns of the coil taken away except one, as in Fig. 16. The needle will still try to set itself at right angles to the plane of the circle of wire, but the field produced by the single turn is not so strong as that of the complete solenoid, and the position taken up will

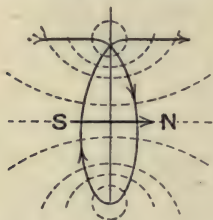


FIG. 16.—Lines of force in a single turn.



FIG. 17.—Lines of force surrounding a straight conductor.

really be a compromise between the axis of the coil and its own free north and south position. Carry the idea further and unwind the coil into a straight wire, and we have, as in Fig. 17, magnetic lines of force running round and round the wire, so that the needle will try to set itself

at right angles to the wire ; and if the current is strong it will actually do so.

This is a most important idea, and it should be clearly understood that **A current is always surrounded by lines of magnetic force at right angles to its direction.**

Deflection of a Magnetic Needle.—A small pivoted magnetic needle can be used, not only to detect the presence of a current, but also to ascertain its direction. For the sake of convenience, place the wire over the pivoted needle lying north and south. Then, if no current is passing, the needle will lie parallel to the wire, but when a current is flowing in the wire the needle will be immediately deflected by a greater or less amount according to the strength of the current. The direction in which it will be deflected is easily remembered by the "**snow**" rule :

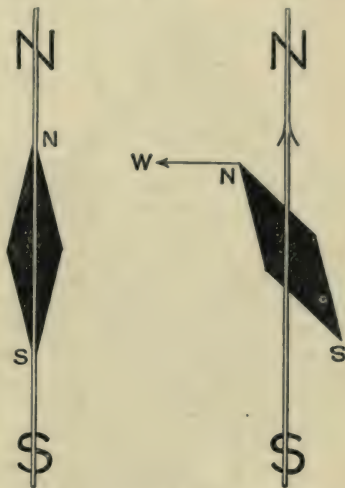


FIG. 18.—Deflection of a magnetic needle.

South to North Over West.

That is to say, when the current is flowing from South to North **over** the needle (and likewise from North to South **under** the needle) the North-seeking pole of the needle will be deflected towards the west. (See Fig. 18.) The effect of course is the same whether a straight wire, a single turn or a coil of many turns is used.

Galvanometers.—This property of a current of being able to deflect a magnetic needle is of great utility, as it furnishes a means not only of detecting but also of measuring an electric current. Instruments for detecting small currents working on this principle are called **galvanometers**.

These usually have coils of many turns, and various methods are employed for showing the movement of the needle. Sometimes a light pointer is fixed to it which moves over a scale, and sometimes the needle

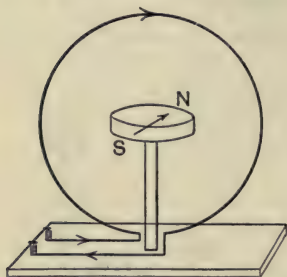


FIG. 19.—The tangent galvanometer.

carries a light mirror which deflects a little beam of light, falling on it from a lamp, so that the movement of a spot of light reflected on to a scale can be seen. One of the simplest kinds of galvanometer, not much used in practice, however, has a large flat coil and a small needle as shown in Fig. 19, and is called a **tangent galvanometer** (because the current is proportional to what is called in trigonometry the *tangent*

of the angle by which the needle is deflected). Another simple form is the **linesman's detector** shown in Fig. 20, where the axis of the needle is horizontal and a more closely fitting coil is used. In what is called an **astatic**

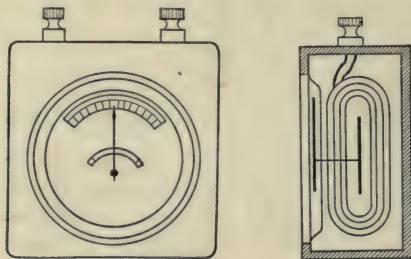


FIG. 20.—The linesman's detector.

galvanometer, a second needle arranged outside the coil in the other direction is used to increase the effect and to neutralise the directive force of the earth's magnetism, so that the only force opposing the deflection is the torsion of the suspension wire or thread.

In another class of galvanometer, the process is reversed; the magnetic part is a large fixed magnet producing lines of force through a small air gap, and the suspended coil surrounding the fixed central iron core is the movable part. These **moving coil instruments** can be made very

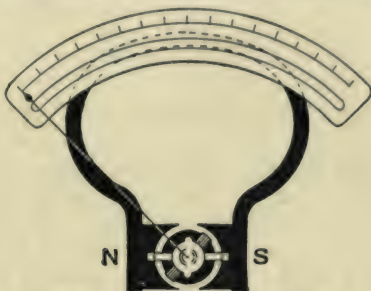


FIG. 21.—Moving coil instrument.

sensitive for dealing with small currents, conveniently measured in **milliamperes** or thousandths of an ampere, or, by means of shunts or series resistances (as in the case of the hot wire instruments mentioned on page 15), may be used as ammeters or voltmeters, that is, graduated to read direct in amperes or volts, as the case may be. One form is shown in Fig. 21. Another class of ammeter very

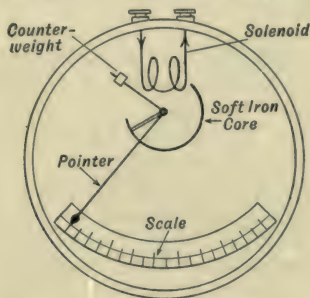


FIG. 22.—Soft iron ammeter.

often used relies for its action upon the pull exerted upon a piece of soft iron by a solenoid (Fig. 21).

CHAPTER IV.

MAGNETISM IN IRON AND STEEL

The Magnetic Circuit.—The path of the lines of force may be looked upon as a magnetic circuit in many ways similar to the electric circuit which we have already considered. The current in the coil may be said to produce a **magnetomotive force**, analogous to E.M.F., and the total magnetic flux (current) which it drives through the circuit depends upon the **reluctance** (resistance) of the material forming the circuit. The part of the circuit composed of iron has far less reluctance than those composed of non-magnetic material (such as air, brass, wood, etc.), and the iron is said to have a much higher **permeability**. The relation between the quantities involved is not quite so simple as Ohm's law of electric currents, and we will consider it at present from a slightly different point of view.

Permeability.—Imagine the solenoid empty; then the current produces a certain number of lines (or tubes, as they are sometimes called) of force which we will denote by H per sq. cm. (H is expressed in units such that one ampere turn per centimetre length of coil induces a field of 1.257 lines per sq. cm.) When the iron is placed inside, we get a greater **flux density** or (**induction**) which we will call B lines per sq. cm. The ratio of B to H is the measure of the **permeability** which is generally denoted by μ (Greek letter *mu*).

Thus
$$\mu = \frac{B}{H} \quad \text{or} \quad B = \mu H.$$

μ varies very much for different qualities of iron

and steel, and even for the same piece of material it is not the same at high and low fields. For air or non-magnetic material, of course, its value is unity.

EXAMPLE.—An iron ring with a mean diameter of 3 inches has 240 turns of wire evenly wound on it as in Fig. 14 (*d*). Now the mean circumference will be approximately $3 \times \frac{22}{7} = 9.43$ ins., or approximately 24 cm., so that there will be 10 turns per centimetre. A current of half an ampere will give a magnetising force (*H*) of 6.28 lines per sq. cm. Suppose that the kind of iron which we are using has a permeability of 1500 at this magnetising force, then the induction (*B*) would equal $1500 \times 6.28 = 9450$ (approx.).

The Molecular Theory of Magnetism.—We will now look a little more closely into what happens within the iron when it becomes magnetic. A very interesting view of the subject has been given by Sir J. A. Ewing, who has done more than anyone to make the facts of magnetism clear to us. He based his ideas on the conception that the iron is made up of a great number of little particles, each of which is a little magnet like a compass needle, free to set itself in any direction, but near enough to its neighbours to be affected considerably by their attraction. To study the subject, he constructed a model consisting of rows of little pivoted magnets mounted upon a sheet of glass and watched what happened when they were placed in a magnetic field produced by coils through which a current was passed. When the iron is unmagnetised, or, in the model, when no current is passing in the coils, the little magnets are all “higgledy-piggledy.” The mutual attractions between them form irregular groupings, but there is no general trend for the North poles to point one way or the other. (Fig. 23.) When, however, a

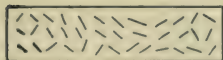


FIG. 23.—Unmagnetised.

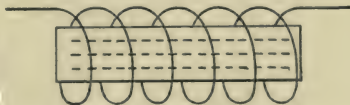


FIG. 24.—Magnetised.

strong field was produced they all pointed the same way, as in Fig. 24, setting themselves along the lines of force, just

as the single needle did on page 20. It is interesting to see what effects are produced as the current is gradually increased in value.

For very low currents, the little magnets just turn their heads, at first slightly, but gradually more and more as the current increases. The little mutual groups begin to break up, as if, in a crowd of people, more and more began to take an interest in a speaker who was addressing them and stopped talking to their friends. Finally all the groups are broken up, as if every one in the crowd had turned and was watching the speaker intently.

Intensity of Magnetisation.—It should not be forgotten that each little magnet has its own lines of force, and that these now acting in the same direction, are reinforcing those produced by the current. A much greater flux is thus produced when the iron is in the solenoid than when it is empty. It is just as if the crowd had joined in the chorus. In magnetic material, the magnetic effect due to the lines of force of such of its own magnetic particles which are pointing together (some if partially magnetised, all if fully magnetised or "Saturated") is known by the name of **intensity of magnetisation**. (**I**) The amount of this effect produced by a certain magnetising force (**H**) varies with the material. An easily magnetised material is said to have a high **Susceptibility** (to magnetisation) and its susceptibility, " κ " (Greek letter *kappa*) is defined as the ratio of **I** to **H**.

We have therefore, $I = \kappa H$.

In air or nonmagnetic material, $\kappa = 0$.

Now the units in which **I** is expressed are such that the lines per sq. cm. due to a piece of iron magnetised to an intensity **I** amount to $4\pi I^1$ (the reason for this is explained later).

The total induction, therefore, made up of the lines rendered available in the iron itself added to those produced by the coil can be expressed as

$$B = 4\pi I + H.$$

¹ π (Greek letter *pi*) means the ratio of the diameter of a circle to its circumference, which is about $\frac{22}{7}$ or more nearly 3.14159.

EXAMPLE.—A rod 20 cm. long has 200 turns of wire wound evenly upon it, that is 10 turns per centimetre, and a current of 0.75 ampere is passed through the winding. This will produce a magnetising force of

$$H = 1.257 \times 10 \times 0.75 = 9.6.$$

Now suppose the susceptibility to be 100, then

$$I = 100 \times 9.6 = 960,$$

$$B = 4\pi I + H = 4 \times \frac{22}{7} \times 960 + 9.6 = 12,000 + 9.6,$$

or approximately, twelve thousand, for with such a high susceptibility the lines due to H are a very small part of the whole induction.

The Magnetisation Curve.—The effect in an actual piece of iron is exactly similar to that on the Ewing model.

If we gradually increase the magnetising force (H), and measure the induction produced (this can be done in a variety of ways, which need not be dwelt upon here), we shall get, on plotting the results together, a **Magnetisation Curve** such as that shown in Fig. 25. In the early part of the curve the particles are beginning to turn round;

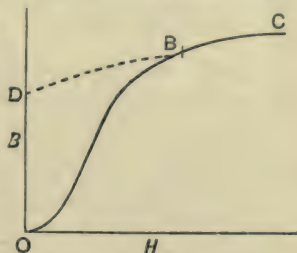


FIG. 25.—Magnetisation curve.

during the steep portion, the groups are breaking up, and on the flatter part BC, practically all have turned round, and the material is approaching saturation.

Residual Magnetism.—Now suppose that when some point, such as B, is reached the magnetising current is gradually reduced to nothing, *i.e.* H is reduced to zero. The result will not be to reduce B to zero, but it will only drop to a slightly lower value OD, that is to say, the iron retains a considerable proportion of its magnetisation. Thus OD is said to represent the **residual magnetism** in the iron. The old haphazard groups that we saw in the Ewing model do not reform, as if, in our analogy of the crowd most of the members still faced towards the speaker although he has ceased to speak.

Hysteresis.—Let us now apply a gradually increasing magnetic force in the opposite direction. The course of

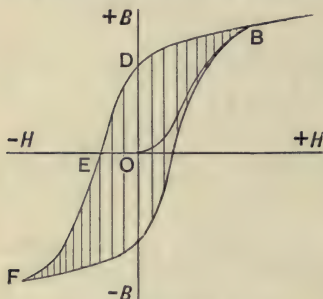


FIG. 26.—Hysteresis loop.

events is represented in Fig. 26. It is not until E that the magnetisation is removed completely, and OE, which represents the magnetic force required to demagnetise the iron, is called its **coercive force**. The curve follows on to F, where H reaches its full negative value, when the material is magnetised again to the same extent that it was at B but in the opposite direction. Reducing H to zero and increasing it again in the positive direction to its value at the point B, makes a similar but inverted curve. We now see that when the iron is carried round what is called a **cycle of magnetisation**, the magnetism produced lags behind the force producing it. To this effect Ewing gave the name **hysteresis**.¹ This property of iron is of considerable importance, as the area of the closed hysteresis loop (shaded in Fig. 26) represents the work done in carrying out the change in magnetic condition.

Magnetism and Temperature.—It may be remarked here that the magnetic properties of materials are considerably affected by temperature. A moderate increase of temperature in iron and steel as a rule slightly improves its permeability under weak fields, but lowers it under strong fields, and diminishes its hysteresis; but at a bright red heat its magnetic properties disappear altogether.

Retentivity.—How much of the residual magnetism, which remains in the iron after the current is discontinued, can be retained permanently, depends upon the properties of the material. Very soft iron, although more easily magnetised by the current surrounding it than hard steel

¹ From Greek words meaning a lagging behind.

(that is, of higher permeability), has small coercive force and its residual magnetism is not easily retained ; indeed, the slightest blow or vibration will cause it to disappear ; just as in Ewing's model, if we gradually reduce the current to zero, the little magnets that remain arranged in neat lines are sent all higgledy-piggledy again if we tap the glass, and the members of our crowd soon begin to talk to one another when the speaker departs. Hard steel, on the other hand, has greater coercive force, and the little particles are not so easy to move round ; so, once magnetised, it retains a large proportion of its residual magnetism, forming what we call a **permanent magnet**.

CHAPTER V.

THE PERMANENT MAGNET.

The Permanent Magnet.—Permanent magnets were known, and their properties had been investigated to a considerable extent, long before electric currents, or the magnetic fields produced by them were discovered. But we have purposely considered the subject first in connection with electric currents, as it is a great help to the student to think of magnetic lines of force as always existing where a current is flowing and indeed as forming part and parcel of the same phenomenon.

The Lode-stone.—Pieces of a magnetic mineral, an oxide of iron called magnetite, are sometimes found in nature already strongly magnetised. Such natural permanent magnets were known to the ancients and their property of pointing to the north star or **lode-star** when suspended was known at a very early date. Hence they were spoken of as **lode-stones**.

Terrestrial Magnetism.—The whole of the earth really forms a great magnet, but no one knows precisely how it came to be originally magnetised. Its magnetic poles do not lie exactly at its geographic north and south poles, although they are near to them. There is thus a magnetic field over the whole of the surface of the globe, with lines of force running roughly north and south. It is not a very strong field (H in a horizontal direction is about 0.18), but is quite sufficient to attract the poles of a compass needle and to make it point to the magnetic north pole. The amount by which the magnetic north deviates from true north varies in different parts of the world and also varies from time to time, as the magnetic poles are always

slowly changing their position. The deviation from the true north is called **magnetic declination or variation**. Its value and the way in which it is changing is fairly accurately known and sailors anywhere can tell how much to allow to give them a true north and south direction. Compasses can also be checked by observations of the stars. The magnetic declination in England is now about 14 degrees West. Neighbouring masses of iron, including the material of a ship's hull, affect the compass a good deal, but other masses of iron can be placed near to the compass and adjusted to compensate for this effect.

It will readily be seen that the magnetic lines of force do not travel flat along the surface of the earth at all parts of the globe; hence a needle free to take up any position in a vertical plane will set itself not horizontally but at an angle. This angle is called the angle of **dip**, or sometimes the **inclination**. In England, the angle of dip of the north pole of a compass needle is about 67° below the horizontal.

Magnetic Attraction.—Magnets are recognised by their property of attracting other pieces of iron, whether these have been previously magnetised or not. This is because the lines of force forming its field induce magnetism in pieces of iron placed in the field, making them temporary (or, in the case of hard steel, permanent) magnets, with the poles at such a point that the pole nearest the inducing pole is of opposite polarity to it and therefore is attracted by it.

Magnetic fields.—A good deal can be learned about the distribution of the lines of force from a permanent magnet by laying the magnet under a sheet of paper or of glass and powdering iron filings thereon, as was done in the case of electromagnetic fields. Some examples of the effect produced are given in Figs. 27 and 28.

Magnetic Poles.—It is not necessary here to consider the theory of the distribution of the earth's magnetic field or the magnitude of the forces of attraction and repulsion exerted upon one another by magnetic poles at any great length, but we will confine ourselves to a few

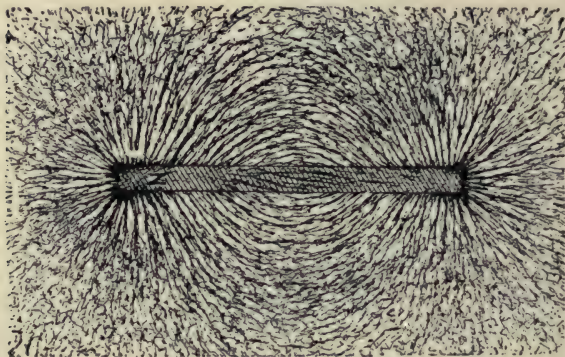


FIG. 27.—Field of bar-magnet.

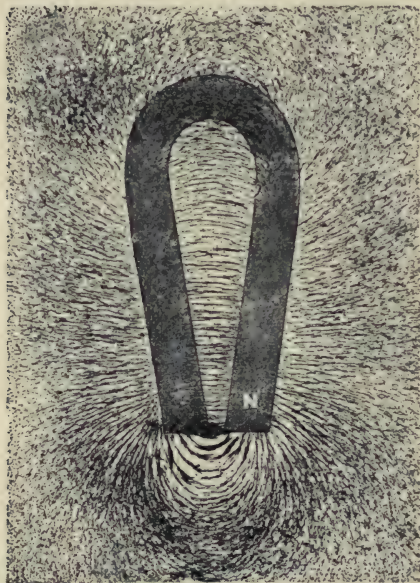


FIG. 28.—Field of Horseshoe magnet.

fundamental ideas. These form a rather different way of looking at the subject from that which has been already outlined, and were developed quite apart from the idea that magnetic lines of force had anything to do with electric currents.

The first conception is that of **strength of pole**. Of course, one pole cannot exist alone as there must be an opposite one at the other end, or at any rate at some other point, of the magnet. The nearest approach to a single pole that we can realise in practice is one end of a very long steel magnet like a knitting needle with a bicycle bearing ball fixed to each end. Thinking then of a single pole concentrated at one point, a **Unit Pole** is defined as **a pole which repels a similar pole at a distance of one centimetre from it with a force equal to one dyne.**¹

The force between two poles is proportional to the product of their strengths and is inversely proportional to the square of the distance between them; or as an equation

$$F = \frac{m_1 m_2}{d^2} \text{ dynes.}$$

The strength of a field or its Intensity is measured by the force in dynes exerted upon a unit isolated pole at that point.

A unit magnetic field defined in this way, has one tube of force per square centimetre section. Thus the intensity of a field at any point may be measured by the number of unit tubes of force per sq. cm. at that point. Some writers use the name **gauss** for the unit of magnetic field strength.

EXAMPLE.—The force exerted between two poles of strength 50 and 90 units respectively placed 10 cm. apart

$$= \frac{m_1 m_2}{d^2} = \frac{50 \times 90}{100} = 40 \text{ dynes.}$$

Magnetic Intensity.—It is important to note that when the lines are considered as coming out in all directions from an ideal pole consisting of a point in space, the intensity of the field at all points on the surface of a

¹ A dyne is a force which, if applied to one gramme for 1 second, produces a velocity of 1 cm. per second.

sphere of one centimetre radius is unity or one tube of force per sq. cm. Now the total surface of this sphere is 4π sq. cm., so that the total number of tubes of force emanating from unit pole is 4π . These unit tubes are exactly the same as those considered before when dealing with magnetic flux and flux density; and the above way of looking at the subject should make it clear why the mysterious 4π appears in the formula $\mathbf{B} = 4\pi\mathbf{I} + \mathbf{H}$ on page 26; for the lines of force per sq. cm. passing through a piece of iron magnetised with an intensity $\mathbf{I}$. It is obvious that the number of lines of force passing through the iron is the same as the number emanating from its pole.

Magnetic Moment.—For the sake of simplicity the theory of a single pole has been considered, but in practice we more often have to consider the forces from both poles of a magnet together, particularly when dealing with a short magnet. The simplest case (Fig. 29), is that of a

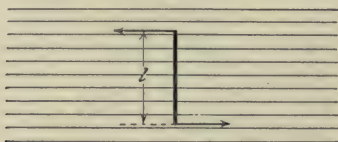


FIG. 29.—Pivoted needle in uniform field.

pivoted needle of length l and pole strength m , in a magnetic field $\mathbf{H}$. The couple tending to twist the needle round is $ml \times \mathbf{H}$.

To the quantity ml , that is the product of the pole strength and the distance between the poles, the name **magnetic moment** is given. It can be shown that the magnetic moment per unit volume is equal to its intensity of magnetisation, which, we have already seen, is equal to the pole strength per unit area.

EXAMPLE.—The couple tending to deflect a needle 5 cm. long with a pole strength of 10 units at right angles to a field $\mathbf{H} = 8$, is $ml \times \mathbf{H} = 10 \times 5 \times 8 = 400$ dyne-centimetres, and the magnetic moment of the needle will be 50 units.

CHAPTER VI.

FORCES EXERTED BY CURRENTS. THE ELECTRIC MOTOR.

Forces between Currents and Magnets.—It has been shown that magnets, whether they are permanent magnets or electro-magnets, exert mechanical forces upon each other; and that the magnetic field produced by a current exerts force upon a magnet placed in its neighbourhood. Examples have been pointed to both where a fixed coil causes deflection of a magnetic needle, and where (in a certain class of galvanometer) a fixed magnet causes deflection of a movable current-carrying coil. In fact, however it is produced, one magnetic system exerts force upon another. It is not necessary for iron or other magnetic material to be present.

Forces between Currents and Currents.—Consider two electromagnets as in Fig. 30, in line with each other and

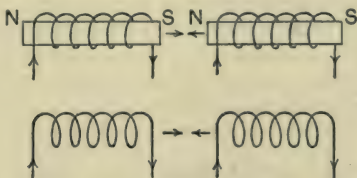


FIG. 30.—Attraction of solenoids.

with their opposite poles adjacent. We know that a powerful attraction will draw them together. Now take away the iron cores; we have still a magnetic field,

although it is not so strong as before and we still have attraction between the empty solenoids. The currents in the turns of wire attract each other and the actual wires carrying them are drawn together. Now consider one

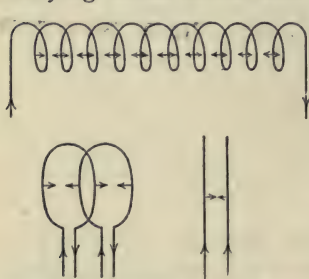


FIG. 31.—Attraction between parallel currents.

long coil or solenoid (Fig. 31), instead of the two separate coils; each turn will attract the one next to it, in exactly the same way as the neighbouring solenoids did, and indeed if the coil is loosely wound of flexible wire it will actually contract and close up. Imagine the coil unwound into a straight wire, as was done when considering the lines of force due to

a straight current, and we see clearly that parallel currents flowing in the same direction attract each other. In like manner, currents in opposite directions repel each other.

Unit of Current.—The force exerted by currents on magnets and on each other furnishes a means of arriving at a method of defining and measuring current strength. The simplest way is to consider the force exerted by a current on a turn of wire of one centimetre radius, and to take as unit a current every centimetre length of which exerts a force of one dyne on a unit pole at its centre. That is the same as saying that each centimetre contributes one unit to the field at its centre. For theoretical purposes this was done, but the unit thus arrived at (called the absolute electromagnetic unit of current), was thought to be too large to be convenient, and the practical unit, the *ampere*, was chosen as one tenth of the absolute unit.

Forces due to Circular Coils.—The idea is made clearer by reference to Fig. 32. AB is one centimetre length of a circular current of one centimetre radius producing unit field at O and exerting a force of one dyne upon a unit pole in the direction shown by the arrow. Now the complete circle will measure 2π cm.; so that the strength

of field at the centre due to the whole turn will be 2π . Thus one ampere-turn, with a radius of one centimetre, will produce a field at the centre of $\frac{2\pi}{10}$ units. If the radius be r cm. the circumference will be $2\pi r$ cm. and, as the force exerted varies inversely as the square of the distance, the force on unit pole (that is the field strength) at the centre will be $\frac{2\pi r}{10r^2} = \frac{2\pi}{10r}$, therefore, if there are n turns each carrying a current of I amperes,

$$H = \frac{2\pi n I}{10r}.$$

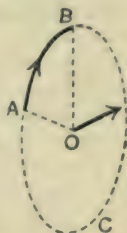


FIG. 32.—Force due to a circular current.

EXAMPLE.—What is the force on a magnet pole of a strength of 15 units at the centre of a coil of 20 cm. radius of 100 turns carrying 0.25 amperes?

$$15 \times \frac{2\pi n I}{10r} = \frac{15 \times 2 \times 22 \times 100 \times 0.25}{7 \times 10 \times 20} = 11.8 \text{ dynes.}$$

Forces due to Parallel Currents.—The attraction between parallel currents is proportional to the product of their strengths divided by the distance between them. Thus, the force per centimetre length between two currents I_1 and I_2 amperes, r cm. apart, can be shown to be $\frac{2 \times I_1 \times I_2}{r \times 100}$, or a circuit carrying one ampere exerts a force of $\frac{1}{50}$ dyne upon a parallel circuit one centimetre from it, also carrying one ampere.

The forces between straight currents unassociated with iron are small unless the currents are very large. In the case of heavy short circuits they may be sufficient to cause damage to the apparatus.

EXAMPLE.—Two parallel wires, 10 cm. apart, carry currents of 10 and 15 amperes respectively. What is the force on 5 cm. length of each wire?

$$\frac{2I_1 I_2}{r \times 100} \times 5 = \frac{2 \times 10 \times 15}{10 \times 100} \times 5 = 1.50 \text{ dyne.}$$

Several instruments depending on the attraction of current carrying coils for the measurement of currents have been designed.

The Electric Motor.—It was early realised that the forces exerted by electric currents could be turned to useful account for converting a supply of electrical energy into motive power; and a variety of arrangements were designed wherein the attraction of electro-magnets was utilised in this way.

The principle of the modern **electric motor** will be understood from Fig. 33. The single turn coil of wire AA is

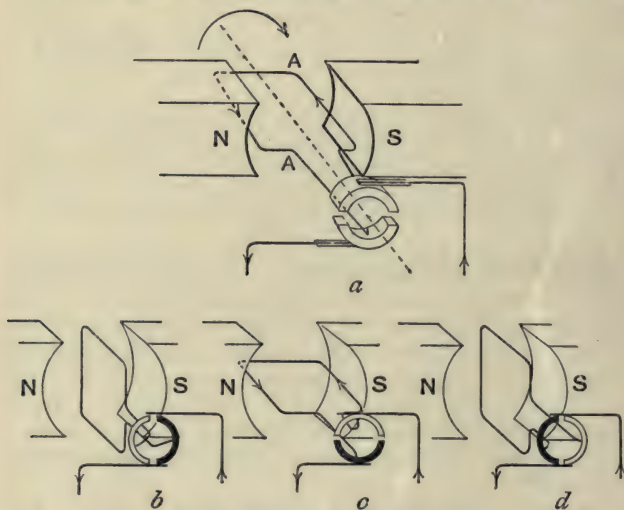


FIG. 33.—Principle of the electric motor.

arranged on an axle so as to be able to rotate in the field of the electro-magnet of which the poles are shown at N. and S. When the coil is carrying a current, it will endeavour to set itself at right angles to the field, acting exactly like a very short wide magnet. Consequently, when it is in the position *a* it will have a force exerted on it tending to draw it into position *b*, and will turn in the

direction of the arrow. If, therefore, it can be arranged that the current in the half of the coil next to each pole is always in the same direction, the pull on the coil will always be in the same direction. This is done by bringing the ends to a divided ring upon which two metallic brushes press and conduct the current in and out. A study of the four positions of the coil in Fig. 33 will show how the current comes to be always in the right direction in the coil as it comes round.

The moving part carrying the coil is called the **armature**, the electro-magnet is called the **field magnet**, and the split contact ring is called the **commutator**.

In practice such a single coil armature would be inconvenient. The forces exerted at different parts of the revolution are very unequal and there are certain dead points where no force is exerted at all. An arrangement of several coils at different angles spaced all round is used, as in Fig. 34. A commutator of several sections is employed, and as much iron as possible is provided in the path of the lines of force, to obtain a high magnetic flux. The coils are

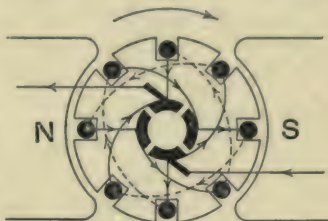


FIG. 34.—Armature with four part commutator.

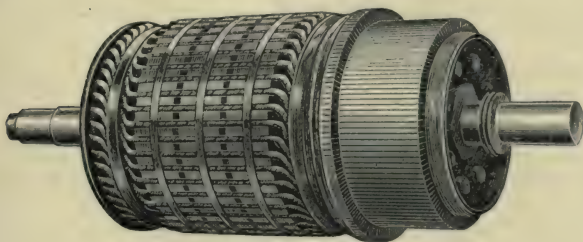


FIG. 35.—Complete armature.

therefore contained in slots in an iron core which fits between the hollowed poles with only a very small air gap

between. In practice, each coil usually consists of several turns. A complete armature made in this way is shown in

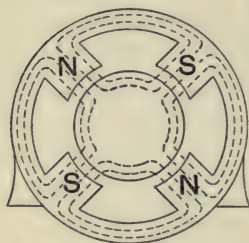


FIG. 36.—Diagram of a four pole machine.

Fig. 35. The principle is exactly the same as in Fig. 33, only more coils are employed to obtain an even torque.

The shape and arrangement of the field-magnets varies considerably in different designs of motors. In some, four magnet poles are used instead of two with the flux between any two going only through a part of the armature, as in Fig. 36. In larger machines a considerable number of inwardly radiating poles are used. Motors with more than two poles are called **multipolar** machines.

Armature and Field Connections.—There are several alternative ways in which the armature and field-circuits can be connected up. In some motors the field coils are in series with the armature. These are called **series motors**. In others the armature and field are in parallel. Those which are more widely used are called **shunt motors**. In another class, called **compound wound motors**, the field magnets have both shunt and series windings. It will be convenient to discuss the characteristics of these different arrangements after the action of the dynamo has been considered.

Efficiency of Motors.—If an electric motor were a perfect machine, the whole of the energy of the current put into it would re-appear as mechanical work. For example, a motor taking 10 amperes at 100 volts, that is 1000 watts (or one kilowatt), would give out $\frac{1000}{746} = 1.34$ horse-power. There are, however, certain unavoidable losses of energy in the machine; these include the heating of the windings due to their resistance (I^2R), the hysteresis of the armature iron, which is carried round a cycle of magnetisation as it revolves, and friction of the brushes and bearings. Suppose in the above case that 150 watts are absorbed

in the machine in this way, then only 850 watts remain to be converted into mechanical power, giving $\frac{850}{746} = 1.07$ H.P. Such a motor would be said to have an efficiency of 85 per cent. as only 85 out of every 100 watts are turned to useful account.

EXAMPLE.—A motor is required to run on a 500 volt circuit and to give 60 H.P. Assuming its efficiency to be 87 per cent., what current will it take at full load?

60 H.P. is equivalent to $60 \times 746 = 4476$ watts. Therefore the total watts required = $\frac{4476 \times 100}{87} = 5145$ watts. The current will be $\frac{5145}{500} = 1.025$ amperes.

CHAPTER VII.

CHEMICAL EFFECTS OF THE CURRENT. BATTERIES.

Chemical Effects of a Current.—In the preceding chapters, it has been seen that an electric current is capable of producing heating effects, magnetic effects and mechanical force. Another important effect that can be produced by it is the chemical decomposition of a liquid through which the current passes.

Electrolysis of Water.—When a current at a sufficient pressure is passed through water, the water is gradually separated into its two constituents, oxygen and hydrogen, and these appear in bubbles on the metal surfaces or **electrodes** which conduct the current to and from the water.

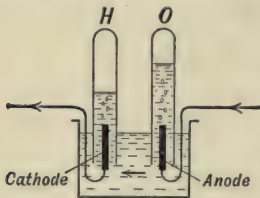
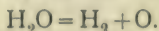


FIG. 37.—Electrolysis of water.

These gases can easily be collected by being allowed to bubble into tubes over the electrodes. An apparatus for this purpose, sometimes called a **voltameter**, is represented diagrammatically in Fig. 37. The hydrogen appears at the electrode where the current leaves the liquid, called the **cathode**, and the oxygen

appears at the electrode where the current enters the liquid, called the **anode**. This chemical action thus furnishes a means of finding out in which direction the current is flowing. The cathode is easily recognised because the volume of hydrogen appearing in a given time is twice the volume of the oxygen given off; for,

as is well known, water is composed of hydrogen and oxygen, combined together in the proportion of two volumes of hydrogen to one of oxygen. In chemical symbols the action is represented as :

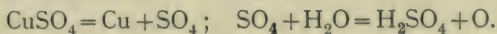


The **electrolysis** of water, as it is called, also furnishes a means of measuring the strength of the current, as a definite quantity of water is decomposed by each ampere of current during each second that it flows, and a definite quantity of hydrogen (0.001044 gramme) is given off.

In practice, it is found necessary to add a little acid to the water, since pure water is not a very good conductor, but this does not affect the action. It should also be remarked that if the gases given off are measured accurately, the amount of hydrogen given off is found to be a little more than twice that of the oxygen, because a small portion of the oxygen is given off in the denser form of ozone. It is also important that the electrodes be made of some such material as platinum which is not chemically acted upon by the gases as they are produced.

Electrolysis of water is actually made use of for current measurement in one form of electric supply meter and the process on a large scale with powerful currents has been employed for making oxygen, as well as hydrogen for balloons and other purposes.

Electrolysis of Solutions of Metallic Salts.—Other liquids or **electrolytes** are also decomposed by the current, but the action is not always quite so simple. A solution of copper sulphate, for example, which is composed of copper, sulphur and oxygen (with the chemical symbol CuSO_4) is split up into copper, which appears as a coating on the cathode and an unstable compound of sulphur and oxygen (SO_4), sometimes called sulphion. The latter does not, however, appear intact at the anode, but reacts upon the water, producing oxygen which bubbles off and sulphuric acid (H_2SO_4) which remains in the solution. Expressed in chemical symbols,



The action in this form can only take place when the electrodes are of platinum or other material not acted upon. If the electrodes are of copper, the sulphion, instead of attracting the hydrogen from the water, dissolves away the copper of the anode, making fresh copper sulphate. The effect is that copper, from the anode, is sent through the solution by the current and deposited upon the cathode. Just as is the case of hydrogen separated from water, a definite amount of copper (0.0003293 gramme) is deposited by every ampere during each second that it flows.

Electro-deposition of Metals.—The same action takes place with other metals. Silver can be deposited from solutions of silver salts, and this process is largely used in **electroplating**. All that is done is to provide a plate of silver to form the anode immersed in a tank, containing a suitable solution, and to hang up the articles to be plated from metal hooks, to form the cathode, and to connect them to a suitable source of current. In this case the current is large but is at a low pressure. The nickel plating of bicycle parts, etc., is carried out in exactly the same way. Another example of **electro-deposition** of metals is the process of **electrotyping**, in which copper is deposited on a matrix or mould made from the printing type, block, or other object which it is desired to reproduce in copper. It is generally convenient to make the mould of a pliable material such as gutta-percha, and in this case, the surface has to be made conducting by giving it a coating of graphite (black lead).

Laws of Electrolysis.—It has been seen that a definite amount of a substance is deposited by every ampere during each second that it passes. This amount is called the **electrochemical equivalent** of the substance. For example, the electrochemical equivalent of silver is 0.0011183 and that of copper is 0.0003293. A convenient way of looking at the matter is to regard the passage of one ampere for one second as the passage of a unit **quantity of electricity** and to this the name of one **coulomb** has been given. We can then say that the passage of one coulomb

will deposit 0.0011183 gramme of silver or 0.0007293 gramme of copper and so on. So that the electrochemical equivalent of a substance is the amount of that substance deposited by each coulomb that passes. The weight of a substance deposited is, thus equal to zIt , where z = the electrochemical equivalent, I = the current in amperes, and t = the time in seconds.

If several **electrolytic cells**, or voltmeters, are coupled in series, the same amount of the substance is deposited on the cathode of each, because the same current is passing through all the cells.

EXAMPLE.—How much copper will 100 amperes deposit in one hour in a single cell?

$$w = zIt = 0.0007293 \times 100 \times 60 \times 60 = 263 \text{ grammes.}$$

Pure copper for electrical purposes is prepared by an electrolytic method; and many other electrolytic processes are made use of in metallurgy and chemical manufactures. Weighing the deposit of silver on the cathode of a silver voltmeter forms an accurate way of measuring steady currents to check other current-measuring instruments.

Theory of Electrolysis.—An interesting way of looking at the subject of electrolysis is to consider the electrolyte as being made up of chains of molecules, composed of two easily separated parts which we will call positive and negative **ions** respectively. The effect of the current is to cause a procession of negative ions to be carried towards the cathode, changing partners on the way (like the old dancing figure of the ladies' chain), and finally arriving free at the electrodes. Indeed, it may be conceived that in their migration the ions carry with them minute quantities of electricity and that this really forms the current in the electrolyte.

Reversibility of Electrolytic action.—It has been seen that an electric current can produce a splitting up of chemical substances and it is found that the reverse action is also possible, for a recombination of the electrolied constituents can cause a counter procession of ions and produce a current. The case of the electrolysis of

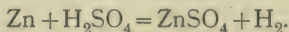
water is not a very practical one to take, but it will serve to illustrate the theory. With suitable electrodes of such a material as spongy platinum, capable of absorbing or occluding the gases, a current can actually be produced by the recombination of the hydrogen and the oxygen in an apparatus very similar to that in Fig. 37.¹ In fact, the apparatus may be said to form an **accumulator** of the energy of the current put in during the electrolysis of the water. It is stored up in the form of the chemical energy of the separated oxygen and hydrogen, and can be given out again in an electrical form if the gases are allowed to recombine. The attraction of the oxygen and hydrogen waiting to combine produces an E.M.F. of about one volt. When the circuit is completed, a current flows and an amount of hydrogen corresponding to that liberated per coulomb, during electrolysis, will be recombined for each coulomb given out. It is owing to this E.M.F., that in order to effect the decomposition of water an E.M.F. higher than a certain value has to be employed to fight against and to overcome the **back electromotive force** of the oxygen and hydrogen trying to recombine.

Accumulators.—The principle of the electric accumulator cell is similar, except that use is made of a more complicated chemical reaction. An accumulator cell of the usual kind consists of two interleaved sets of lead plates, or grids, forming positive and negative electrodes immersed in dilute sulphuric acid. The plates are packed with a paste of red lead (an oxide of lead with the chemical formula Pb_3O_4). The action of the current passed into the cell, or the **charging current**, is to reduce the paste to spongy metallic lead on one plate and to oxidise it further into PbO_2 on the other plate. These two chemically different substances, like the oxygen and hydrogen in the case of water, tend to return to their original states, and in doing so can give out the energy that has been stored. A lead accumulator of this kind gives a discharge voltage of a little over 2 volts and a slightly higher voltage is of course necessary for charging. Any number

¹ This arrangement is known as Grove's gas battery.

of such **accumulator** cells can be connected in series to form an accumulator **battery** to produce any desired voltage, or rather any desired multiple of the voltage of a single cell. Such an accumulator is sometimes called a **Secondary Battery**. It is usual to define the size of an accumulator cell by the number of **Ampere-Hours** that it can store. Thus a cell of a capacity of 50 ampere-hours could give a current of five amperes for 10 hours, or of 10 amperes for 5 hours.

Primary Batteries.—The secondary battery has been described first owing to its aptness as an illustration of the reversibility of transformations between electrical and chemical energy, but there are other and simpler chemical actions which can produce electric currents, but which are not reversible. The simplest form of cell for producing electric currents by a purely chemical method consists (Fig. 38) of a plate of zinc and a plate of copper dipping into dilute sulphuric acid. An electro-motive force of about 1.03 volts exists between the plates and if they be joined by a conducting path to complete the circuit, a current will flow from the copper to the zinc in the outside circuit, and consequently from the zinc to the copper through the liquid electrolyte. The chemical action that takes place consists in the zinc being dissolved in the sulphuric acid, producing zinc sulphate and liberating hydrogen at the surface of the copper ; or, in chemical symbols,



Almost any pair of dissimilar metals will show the effect, and for every pair of metals a definite E.M.F. is produced. There is considerable choice as to the liquids which may be used as electrolytes. Metals, etc., can be arranged in a list with those most **electro-positive**, as it is called, at one end and those most **electro-negative** at the other. The further apart the metals are on this list the greater

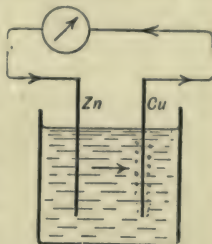


FIG. 38.—Voltaic cell.

will be the E.M.F. produced between them. Zinc and carbon, for example, give a slightly higher E.M.F. than the zinc and copper of the original cell discovered by Volta, and in modern batteries they form the pair most frequently used.

Polarisation.—It was noticed above that hydrogen bubbles appeared on the positive pole. The presence of these somewhat weakens the current, not only because it increases the internal resistance of the cell, but because it causes a back E.M.F. to be produced. The cell when weakened in this way is said to have become **polarised**. The usual method of preventing polarisation where a carbon positive is employed is to provide a chemical substance of an oxidising nature, such as manganese dioxide, round the positive pole to supply oxygen to combine with the hydrogen as fast as it is formed. Another method is to add the oxidising agent, or **depolariser**, to the electrolyte. Potassium bichromate is sometimes used for this purpose.

In one type of cell (the Daniell cell), used at one time for telegraph work, a copper sulphate solution is provided round the copper pole separated by a porous pot from the sulphuric acid, or other electrolyte, round the zinc. In this case, the hydrogen exchanges itself for the copper in the copper sulphate and copper is deposited instead of hydrogen, with no harmful effect. It is not proposed to describe here all the various forms of primary cell that have been introduced from time to time.

Zinc is the negative pole in practically all primary cells and the energy of the current is derived from its gradual consumption. Zinc is the fuel and its solution or "burning away" supplies the energy. It is, however, a somewhat expensive fuel to burn, and with the exception of producing current on a very small scale, cheaper methods have come into use. Primary batteries are used to a limited extent in telephony and telegraphy, and form a convenient source of current for domestic electric bells and in the familiar pocket lamp or torch.

The battery most used for bells is the Leclanché cell; this is a zinc carbon cell with sal-ammoniac as an electrolyte and a manganese dioxide depolariser, usually

enclosed in a porous pot surrounding the carbon rod forming the positive pole. A very popular variation is the so-called **dry battery** in which the sal-ammoniac is made up with other substances into a paste instead of being used in a liquid form; the whole is then enclosed and can be carried about without spilling. The small dry batteries for pocket lamps and torches consist of two or sometimes three of these dry cells in series made up into one package.

Thermo-electricity.—There is another way in which a current can be produced from two dissimilar metals, but this is a thermal rather than a chemical effect. If the ends of two bars, respectively of antimony and bismuth, for example, be soldered together and their free ends connected to a circuit containing a galvanometer, a current will be found to flow through the joint from the bismuth to the antimony (that is, from the antimony to the bismuth, through the galvanometer) when the joint is heated to a temperature above that of the free ends of the bars. The current will continue to flow as long as the difference of temperature is maintained. If the joint be cooled to a temperature below that of the free ends, a current will flow in the opposite direction.

Different combinations of metals produce different E.M.F.'s, but of ordinary metals the highest voltage that can be produced in this way is that between bismuth and antimony, which is 0.000117 volt per degree Centigrade. To obtain higher voltages, a number of such **thermo-electric junctions** must be connected in series to form a **thermopile**. The method is not practicable for the production of anything except the very smallest currents, but the principle is made use of in one form of electrical thermometer, and in certain instruments for detecting the development of very small quantities of heat.

It is interesting to note that the effect is reversible. If a current is driven by an external E.M.F. through a junction of antimony and bismuth, the joint will be heated, if the current pass through it from the antimony to the bismuth, and will be cooled if it passes in the opposite direction.

CHAPTER VIII.

INDUCED CURRENTS, THE DYNAMO.

Induced Currents.—It has been seen how a current produces a magnetic field, and the question naturally arises whether the action is in any way reversible. It is obvious that the mere presence of a magnet within a coil of wire cannot produce a current in it, as there would be no source for the energy of the current to come from. Faraday, however (in 1831), made the important discovery that while a magnet is being rapidly pushed into a coil, a deflection is produced in a galvanometer connected to its terminals, due to a current being **induced**, as it is called, in the wire. Likewise when the magnet is withdrawn, a deflection is produced in the opposite direction.

This action can be shown in a variety of ways. It makes no difference whether we keep the wire still and move the magnet, or move the wire in a stationary magnetic field. Again, the field need not be that of a permanent magnet, but can be produced by a current in another circuit. Thus, an electro-magnet, or even an empty solenoid, can be used, instead of a permanent magnet. In any case, an E.M.F. is induced in a conductor when there is relative movement between it and a magnetic field, causing it to cut the lines of force: or, to put it in another way, to cause a change in the number of lines of force linked through the circuit.

Direction of Induced E.M.F.—A very convenient rule for remembering the direction of the induced E.M.F. is that known as Fleming's **right hand rule** (Fig. 39), which

is as follows: Let the forefinger of the right hand point in the direction of the magnetic lines, and the thumb in

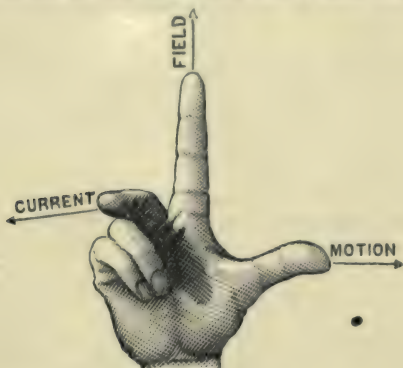


FIG. 39.—The right hand rule.

the direction of motion, then the middle finger bent at right angles to both will show the direction of the induced E.M.F.

Reaction of Induced Currents.—It has already been seen (Chap. VI.) that mechanical force is exerted between a current and a magnetic field. The induced current therefore exerts a reaction upon the field tending to prevent itself being moved. Thus mechanical work has to be done to move a conductor across a magnetic field and to induce a current. The matter is summed up in what is known as **Lenz's law**, which may be expressed as follows: When electro-magnetic induction is caused by mechanical movement, the induced currents bring about forces in such directions that they oppose the motion that produces them.

Induced E.M.F.—When once a unit to measure magnetic field strength has been established, with reference only to mechanical forces, the fact that an induced E.M.F. is proportional to the rate at which magnetic lines of force are cut furnishes a means of arriving at a unit for the measurement of E.M.F. The E.M.F. induced by the cutting of one

line of force per second would be inconveniently small, so the practical unit, the volt, with which we are already familiar, was chosen to correspond with the cutting of 100,000,000 (or as it is more conveniently written 10^8) lines per second. Suppose a wire l centimetres long moves in a magnetic field of strength H so that it cuts the lines of force with a velocity v cm. per second, then the E.M.F. generated will be $\frac{Hlv}{10^8}$.

EXAMPLE.—A wire is 20 cm. long and is moving at a speed of 50 cm. per sec. across a field of 9000 lines per square centimetre. What is the E.M.F. produced?

$$\frac{9000 \times 20 \times 50}{10^8} = 0.09 \text{ volt.}$$

Mutual Induction.—A current can be induced even without any relative motion between the elements, if the field is varied electrically. Thus in the arrangement shown in Fig. 40, closing the key K starts a current in the

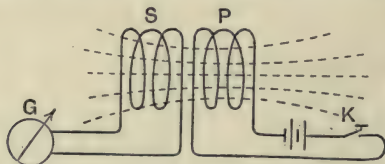


FIG. 40.—Mutual induction.

coil P causing the sudden establishment of a magnetic field, the lines of which pass through the coil S. This is equivalent to thrusting a magnet suddenly into it as in Faraday's original experiment, and a momentary current is observed in the galvanometer G. Likewise, when K is opened, the field ceases to exist, which is equivalent to withdrawing the magnet, and a deflection is obtained in the opposite direction. Indeed, it is sufficient to increase or diminish the current through the primary coil P to produce a current impulse in the secondary coil S. This effect of one circuit upon another is called **mutual induction**. The coefficient of mutual induction, or, to put it more

briefly, the **mutual inductance**, is measured by the number of lines of force produced in the secondary when one ampere flows through the primary.

Self-Induction.—A coil in which a current attempts to start or is interrupted suddenly, produces a similar effect upon itself. So long as the current is increasing, it is superimposing a back E.M.F. upon itself, tending to check its own growth, although when the current is fully established, there is no such effect. Also, when the current is interrupted suddenly, an E.M.F. is produced in the same direction, as if trying to continue the current. The effect, which is called **self-induction**, is analogous to inertia, for the current resists both starting and stopping. The self-induction of a coil is, of course, much greater if it contains iron as more lines of force link the circuit for every ampere flowing. The coefficient of self-induction, or the **inductance**, is measured by the number of lines of force that link the circuit per ampere flowing. The unit of inductance is called the **Henry**.

It is often important that resistance coils be made **non-inductive**. This can be done by winding half in one direction and half in the other, by doubling the wire back upon itself. The currents in the two halves will then cancel each other and no magnetic flux will be produced.

The Induction Coil.—The principle of mutual induction is made use of in the **induction coil**, for the production of very high intermittent voltages. In this case a primary winding of a few turns of thick wire and a secondary winding of a great number of turns of fine wire are wound on the same iron core. The current in the primary is rapidly made and broken over again by an interruptor, on the same principle as the electric bell, or by other means; and owing to the large number of turns, a very high voltage is induced in the secondary.

Eddy Currents.—So far, circuits composed of wires or similar conductors subjected to changing magnetic conditions have been considered. A solid mass of metal, however, in the neighbourhood of a changing current or field has currents induced in it, eddying round in closed

circuits within the material. Thus in the solid iron core of an electro-magnet there are appreciable currents circulating within the iron while the exciting current is growing to its full value, or when it is changed or cut off. The mass of the iron acts exactly like a closed secondary coil. It is to avoid such eddy currents that the core of an induction coil is made of a bundle of separate iron wires, and the iron in the armature of a motor is made up of a number of stampings of sheet iron insulated from one another by paper or varnish.

Another curious effect of eddy currents is seen in an experiment originated by Arago even before Faraday had revealed the existence of induced currents. A rotating copper disc underneath a pivoted magnet was found to drag the needle round with it as if there were some action analogous to friction between them. The experiment was supposed, at the time, to indicate that magnetism could be produced by mere rotary motion, but the effect is purely due to the reaction of the induced eddy-currents. A similar effect is made use of in certain meters and other instruments where a drag is produced on a metal disc moving in the field of a magnet. The energy of eddy-currents is expended in the form of heat.

The Dynamo.—It is readily seen that the production of an E.M.F. in a conductor moved in a magnetic field by the application of mechanical force furnishes a valuable means of generating electric currents. The machine that is employed in this way to turn mechanical energy into electrical energy is called the **dynamo**, and in its construction it is exactly similar to the electric motor described in Chapter VI. Any motor of this class can, in fact, be used as a dynamo and *vice versa*: When the field magnet is excited, every conductor in the armature is moving through a magnetic field and cuts lines of force. An E.M.F. is consequently produced in it and the connections to the commutator cause the current always to be delivered by the brushes in the same direction, just as, when the machine is used as a motor, the current is always in the direction in the armature coils necessary to produce rotation the same way round.

The E.M.F. induced in each conductor in the armature of a dynamo is proportional to the speed at which the armature is running and to the total magnetic flux passing through the armature. There are various ways of arranging the coils in the armature winding with two or more paths in parallel for the current, and as was seen in the case of the motor there can be any number of pairs of poles. Taking all these factors into account and employing convenient units, the E.M.F. of the machine can be shown to be equal to :

$$\frac{\text{Flux per pole} \times \text{Speed} \times \text{number of poles} \times \text{number of} \\ \text{(millions of lines)} \quad \text{(Revs. per min.)} \\ \text{coils} \times \text{turns per coil}}{3000 \times \text{Number of armature circuits}}$$

This is the actual E.M.F., but as in the case of a battery, the internal resistance of the armature causes a voltage drop equal to the current $\times$ the armature resistance. To obtain the terminal voltage V , this must be subtracted from the E.M.F. or in symbols, $V = E - ri$.

Reversibility of the Dynamo and Motor. The action of the dynamo enables us to understand more clearly certain points regarding the working of the motor. When a motor is running, its own coils are cutting through the lines of force, just as in a dynamo, with the consequence that an E.M.F. is being induced in them acting against the E.M.F. of the circuit, or, as it is commonly put, a **back E.M.F.** is produced. This has a very important effect upon the speed at which the motor runs under various conditions. Imagine a machine with a constant field strength and a constant voltage applied to the armature. The machine will run as a motor, and a back E.M.F., which we will call E , is produced corresponding to its speed. E will be less than V and the balance $V - E$ is the voltage drop in the armature due to the current required to provide the forces to overcome the mechanical resistance to motion of the load, the internal friction and other losses. Thus as in a dynamo, $V = E - ri$, so in a motor $V = E + ri$.

Now suppose that the armature is driven by an external agency at a speed higher than it has been running as a

motor. E will then rise and may overtake V , when the machine will behave as a dynamo and pump back current into the line. This effect is sometimes made use of to provide a braking effect in electrically driven vehicles to keep them under control when going downhill, and at the same time to recover power that would otherwise be wasted.

Dynamo and Motor Field Circuits.—In the simplest form of dynamo the field-magnets are formed by permanent magnets. These are called **magneto** machines. They are used on a small scale driven by hand for ringing telephone bells, and also for ignition purposes in petrol and gas engines.¹ Nearly all machines of any size, however, have the field provided by electro-magnets. These can be supplied with current from a separate source, when they are called **separately excited** machines, but it was soon found that this was unnecessary, as the machine could provide its own **excitation** as it is called. Although at the start, there is no current flowing in the field coils, there is always a little magnetism left in the iron of the field-magnets and this is sufficient to produce a small E.M.F. as soon as the armature is started. This small E.M.F. drives a small current through the field coils, raising the magnetic flux, which again increases the current and thus the full field is soon built up, and the machine comes up to its full voltage.

As was briefly mentioned in connection with motors, in Chap. VI., a self-excited machine can be series wound, shunt wound or compound wound.

Series wound dynamos are not much used, as the voltage they give is dependent on the current taken from them and on open circuit they give no voltage at all. Series wound motors, however, have a considerable field of usefulness. At starting and at low speeds they can develop a very high torque, because the large current due to the low back E.M.F. produces a powerful field. As the speed rises, however, the back E.M.F. rises, the current diminishes and, at the same time, the field and conse-

¹ A few old-fashioned magneto machines of larger size are still used for lighthouse work.

quently the torque decreases. These are just the conditions required for tramway and railway purposes as well as for cranes and hoists, where series motors are extensively employed.

The shunt connection is that most often used both for dynamos and for motors. A **Shunt Wound Dynamo** gives a nearly constant voltage, whether giving current or not, when driven at a constant speed, although, when the current increases, the corresponding increase in the voltage drop in the armature causes a certain amount of falling off of the terminal voltage. Similarly, a shunt wound motor, if supplied at a constant voltage, runs at a nearly constant speed although the armature drop causes a certain amount of falling off in the speed at heavy loads. The voltage of a shunt dynamo and the speed of a shunt motor can be regulated to a certain extent by the use of a rheostat or variable resistance in the field circuit. In the case of the dynamo, putting in more resistance diminishes the field and consequently decreases the voltage and *vice versa*; in the case of the motor, putting in more resistance and thereby diminishing the field increases the speed because the armature has to run faster to produce the same back E.M.F.

The effect of armature drop at heavy loads on shunt-wound dynamos is compensated for by adding a few series turns to reinforce the field as the main current increases, and thus converting the machine into a **Compound-wound Dynamo**, which can be made to give a practically constant voltage at all loads without any hand regulation. In the case of a compound-wound motor the series turns are arranged to be in opposition to the shunt field, as a weakening of the field is required to make up for the drop in speed. In this way a practically constant speed can be obtained at all loads.

Control of Motors and Dynamos.—It will readily be seen that if anything except a very small motor be switched suddenly on to the circuit at full voltage, a considerable rush of current would be produced, as, at the time of starting, the back E.M.F. has not yet built up. For this reason, a resistance is always put into the circuit

at starting and is gradually cut out as the speed rises. The starter is also arranged to close the field-circuit before, and to open it after the armature circuit, as there is a risk of a dangerously high rise in speed if an attempt is made to run a motor with no field and consequently no back E.M.F. There are many refinements in the switchgear used for the control of dynamos and motors which cannot be gone into here. Automatic apparatus, for example, is used to break the circuit when the current from any abnormal circumstance becomes dangerously large, and in the case of motor starters the controlling arm is automatically returned to the "off" position in event of a failure of the supply, to avoid any possibility of the full voltage being put on to the motor again without the starting resistance being in circuit. There are also a number of other methods of obtaining speed variation of motors for special purposes.

Output of Dynamos.—The output of a dynamo is measured in kilowatts. The mechanical energy required to drive it has however to be sufficient not only to supply this output but also to make good the various unavoidable losses of energy within the machine. These are made up of the I^2R losses in the armature and the field windings, the losses due to hysteresis and eddy-currents in the iron of the armature and the friction of the bearings and of the brushes. The percentage that the energy given out electrically forms of the energy put in mechanically is called the **efficiency of the machine**.

EXAMPLE.—What horse-power is required to drive a dynamo with an efficiency of 90 per cent. to give 100 kilowatts?

If there were no losses, the required horse-power would be $\frac{100}{0.746} = 134$ H.P. (for 746 watts, or 0.746 K.W. are equivalent to one H.P.). Now the efficiency is 90 per cent., therefore the total horse-power required will be $\frac{134}{0.9} = 149$ H.P. (approx.).

CHAPTER IX.

ALTERNATING CURRENTS.

Continuous and Alternating Currents.—The currents which have been considered so far, flow continually in the same direction and are spoken of as **continuous currents** or sometimes as **direct currents** or **D.C.**, and this is the kind of current produced by a battery or by a dynamo with a commutator, such as has been described in the last chapter. If, however, a dynamo is made without a commutator but simply with **slip rings**, as they are called, connected to the ends of the winding, as shown diagrammatically in Fig. 41, the current given off, instead of being always

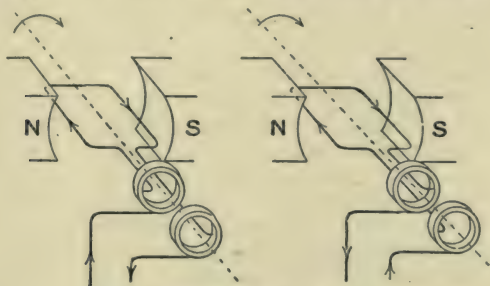


FIG. 41.—Principle of the alternator.

in the same direction, will flow first in one direction and then in the other, because any conductor cuts the lines of force one way during its passage past the north pole and the other way during its passage past the south pole of the field magnet, and delivers the current

straight to the brushes, without any reversal to keep it in the right direction, such as would be provided by the commutator.

A current flowing alternately in one direction and the other in this way has several interesting properties, and is called an **alternating current**, and the dynamo without a commutator which produces it is called an **alternator**. Thus an alternator is really a simpler machine than a continuous current dynamo. Owing to the absence of a commutator, it is possible to arrange the armature winding rather differently. A great variety of types of alternator have been designed, but the pattern that is now most used is like a continuous current machine turned inside out, as the field magnets revolve and are surrounded by a fixed armature with its winding arranged in slots all round. In this case the slip rings are employed only to convey the existing current to the field magnets and not to collect the main current. The field magnets are of course excited by continuous current, which has to be obtained from a separate source; often a small D.C. machine or **exciter** on the same shaft as the alternator. Alternating current is very much used in large power stations and alternators are made up to several thousand kilowatts in output.

Frequency.—It is very helpful to represent an alternating current or the alternating E.M.F. that produces it by a curve as in Fig. 42 showing current in one direction above the axis and in the other direction below it, and plotted against the angle moved through by the coil of a simple two-pole alternator like that in Fig. 41. The current changes its direction once for every half revolution, that is once every 180 degrees and goes through a complete cycle (composed of one wave in each direction) during each complete revolution. The number of cycles gone through in one second is called the **frequency** of the current. In a two-pole alternator the frequency is equal to the speed in revolutions per second. With a greater number of pairs of poles, a correspondingly larger number of alternate North and South Poles are passed by an armature conductor during each revolution and a correspondingly higher frequency is produced for the same speed. Thus,

for an alternator of p poles ($\frac{p}{2}$ pairs of poles), running at a speed of r revolutions per minute ($\frac{r}{60}$ revs. per sec.), the frequency will equal $\frac{r}{60} \times \frac{p}{2} = \frac{rp}{120}$ cycles per second.

EXAMPLES.—1. An eight pole alternator runs at 750 r.p.m., what is the frequency?

$$\frac{8 \times 750}{120} = 50 \text{ cycles per sec.}$$

2. An alternator driven by a steam turbine is required to give 25 cycles per second, what is the highest speed at which it can run?

The smallest number of poles that it can have is two; therefore, the speed will be

$$\frac{25 \times 120}{2} = 1500 \text{ r.p.m.}$$

Phase Angle.—In dealing with alternating currents, it is convenient to retain the arrangement of Fig. 42 quite

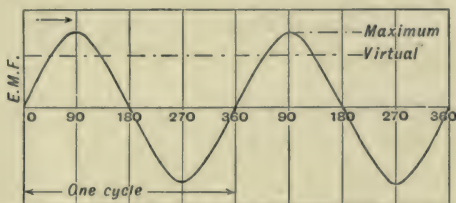


FIG. 42.—Alternating wave form.

irrespective of the number of poles that the alternator generating the current happens to have, and to divide the complete cycle into degrees in the same way. Any part of the cycle can then be described as an angle and this angle is called the **phase angle**.

Those familiar with trigonometry will recognise the curve in Fig. 42 as a curve of sines where the value of the current at any point is proportional to the sine of the phase angle. The form of the E.M.F. wave given by most alternators does not depart very greatly from a true sine curve, so that if V is the maximum value of the voltage, its

instantaneous value at any point in the cycle is equal to $V \sin \theta$, where θ is the phase angle.

It will readily be seen that for alternators to run in parallel, it is necessary for them not only to give the same voltage, as is the case with D.C. machines, but also to be giving exactly the same frequency or, as it is called, to be accurately in **Synchronism**, as well as to be **in phase** with each other, that is giving the same part of the cycle at the same moment. Special arrangements are used to ascertain that this is the case in generating stations before an alternator is switched on to the circuit.

Measurement of Alternating Currents.—It can be shown that the energy of an alternating current (with a sine wave form) is the same as that of a continuous current having a value equal to 0.707 of the maximum value. This is called the **virtual** or the **root mean square** value of the current. Alternating current ammeters and voltmeters read in virtual amperes and virtual volts, and such values are always used for practical purposes. Thus, when we speak of an alternating current at 100 volts, the E.M.F. wave really rises to a maximum of 141.4 volts in each direction.

The Transformer.—The great cause of difference between the behaviour of alternating and continuous currents lies

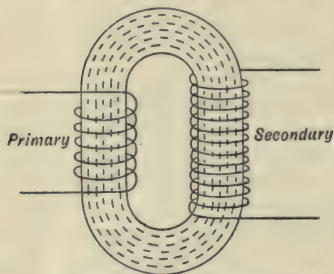


FIG. 43.—The transformer.

in the fact that an alternating current is always changing in value. Now it has been seen in Chapter VIII. that this is exactly the condition required for a current to be induced in a neighbouring circuit. If, for example, an iron core has two windings upon it, as in Fig. 43, and an alternating current is passed through the primary winding,

an alternating E.M.F. will be induced in the secondary winding in exactly the same way as illustrated in Fig. 40

(Chapter VIII.), except that the effect is produced by the natural rise, fall and reversal of the current instead of by making and breaking it rapidly.

Such an apparatus is called a **transformer** and is much used in electrical engineering. The iron core has to be laminated to keep the losses due to eddy-currents as low as possible. The same flux passes through the turns of both windings; consequently, if the secondary has a larger number of turns than the primary a correspondingly higher voltage will be produced. The apparatus can therefore be used to transform a large current at a low voltage into a small current at a high voltage and *vice versa*. It is in the possibility of doing this that the convenience of alternating current working lies.

In the transmission of large powers over long distances, it is most economical to employ very high voltages so that the current in the **transmission line** is as small as possible, to avoid excessive I^2R losses and IR drop, and the necessity for heavy conductors. Before the current is used for power or lighting it can be transformed down to a convenient and safe voltage. Transmission lines are sometimes worked at voltages even over 100,000 volts.

Transformers for stepping down from high transmission voltages to low distribution voltages are often grouped together in **sub-stations**, which feed the **distributing network**, as it is called.

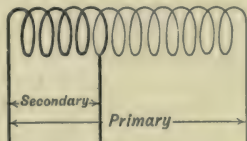


FIG. 44.—The Autotransformer.

It is possible to make a transformer without two independent windings by using a part of the p secondary as the primary or *vice versa* as shown in Fig. 44; such a transformer is called an **autotransformer**.

Effect of Self-Induction.—It was seen, in Chapter VIII., that the effect of self-induction was to put an obstacle in the way of change in the strength of a current by producing an opposite E.M.F. while the change is proceeding, although it has no effect on a continuous current of unvarying value. In the case of an alternating current, the effect of self-induction is to delay the result of the E.M.F. and thus to cause the wave of current to lag behind the wave

of E.M.F. instead of being in phase with it, and also to cause the current to have a lower value than it would otherwise attain if only resistance had to be taken into account.

The effect is made clear by the curves in Fig. 45. It is only in an entirely non-inductive circuit that the waves

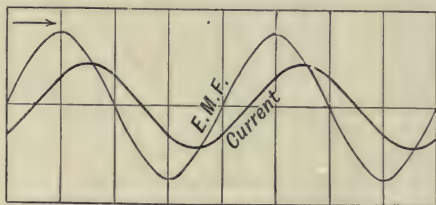


FIG. 45.—Waves of current and E.M.F. in inductive circuit.

of voltage and current are absolutely in phase and that the result is in strict accordance with Ohm's law. The self-induction may be regarded as introducing a **reactive E.M.F.** a quarter of a cycle (90°) out of phase with the **impressed voltage**. In order to calculate the current which a certain alternating voltage will produce in an inductive circuit, we have to take into account, instead of simply the resistance in ohms, a quantity which is called **Impedance** which includes the effect of the reactive voltage or **Reactance** as well as the resistance.

Impedance.—The reactance has the value $2\pi nL$ where L = the self-induction and n = the frequency, but it cannot

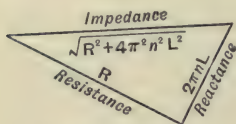


FIG. 46.—Impedance.

simply be added to the resistance (R) because their effects are at right angles in phase. The resistance, the reactance and the impedance may be represented by the sides of a right-angled triangle, as in Fig. 46. Thus the impedance

will be equal to $\sqrt{R^2 + 4\pi^2 n^2 L^2}$ and the virtual current that a virtual voltage E will produce will be

$$\frac{E}{\sqrt{R^2 + 4\pi^2 n^2 L^2}}.$$

Choking Coils.—Coils with or without iron cores, of considerable self-induction, are often used instead of resistances to keep down or to regulate alternating currents. These are called **choking coils**, and are preferable to resistances because they do not waste energy in the form of heat as is the case with resistances. If the core is made movable, the current can be regulated by drawing it in and out and thereby altering the self-induction of the coil.

EXAMPLE.—A choking coil has a resistance of 2 ohms and a self-induction of 2 henrys. What is the current that will be produced by a virtual E.M.F. of 100 volts at 50 cycles?

$$\begin{aligned} \frac{E}{\sqrt{R^2 + 4\pi^2 n^2 L^2}} &= \frac{100}{\sqrt{4 + (4 \times 9.86 \times 2500 \times 4)}} \\ &= \frac{100}{627} = 0.16 \text{ amperes.} \end{aligned}$$

Power-factor.—Another way of looking at the subject is to regard the current as the resultant of two components, (1) an active current in phase with the impressed voltage and (2) a reactive current at right angles in phase to it. These currents can be represented by the sides of a triangle, as in Fig. 47, where θ is the **angle of lag** of the current behind the E.M.F. The component in phase with the voltage is that which must be multiplied by the voltage to give the true power in the circuit in watts. The other component is sometimes described as a **wattless current**. The ratio of the power component to the wattless or idle component is called the **power-factor** of the circuit, and is equal to the cosine of the angle of lag. Thus the true power is equal to the virtual voltage $\times$ the virtual current $\times$ the power-factor.

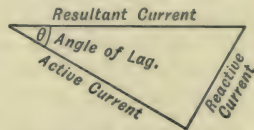


FIG. 47.—Active and reactive currents.

EXAMPLE.—A 500 volt alternator is supplying 20 amperes to a circuit, with a power-factor of 0.75. What is the true power in the circuit?

$$\frac{500 \times 20 \times 0.75}{1000} = 7.5 \text{ K.W.}$$

The power in the circuit is thus 75 k.w. instead of the 10 k.w. which it would be at unity power-factor.

Such an alternator would be said to be giving 10 **kilo-volt-amperes** or **k.v.a.**

Another property called **capacity** can also be possessed by a circuit, to which attention will be called more fully later. This has the reverse effect from self-induction, in that it facilitates the start of a current and causes an alternating current to lead instead of to lag with relation to the voltage, thus giving the circuit a *negative* power-factor.

A.C. Electro-magnets.—If an alternating current is used to excite an electro-magnet, a rapid reversal of its poles is produced, but pieces of iron will still be attracted as corresponding rapidly alternating poles will be induced in them. An alternating current electro-magnet has however the further property of inducing eddy-currents in masses of metal in its field, and these are always in the direction contrary to the current in the exciting coils at any moment, that is, in the direction to cause repulsion by the field of the magnet. Thus, if a light copper or aluminium ring be placed over the extended pole of an A.C. electro-magnet and the current suddenly switched on, the ring will be repelled and if the magnet is powerful enough, will be thrown up into the air.

Polyphase Currents.—If, instead of taking two points from an armature winding and connecting them to slip

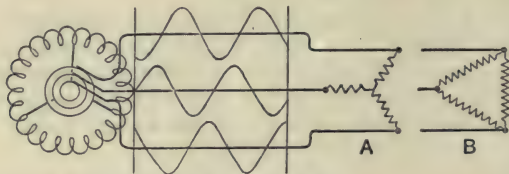


FIG. 48.—Three-phase currents.

rings, so as to produce what is called a **single-phase** current in the way that we have been considering, three equidistant points are taken and connected to three slip rings,

we can obtain three currents in three branches of a triple circuit, each 120° out of phase with its neighbour in the way shown in Fig. 48, when these branches are joined up again, either by a **star** connection as at A or what is called a **mesh** connection as at B. For various reasons, a **three-phase** arrangement of this kind is more widely used for electric power transmission than the simple single-phase system. In a similar way, a **six-phase current** could be obtained from six slip rings. A **two-phase** arrangement with four wires is also sometimes used. Currents with several branches or **phases** of this kind are called **polyphase currents**.

Alternating Current Motors.—Consider a three-phase current produced by an alternator A with a two-pole revolving field-magnet as represented in Fig. 49, with the

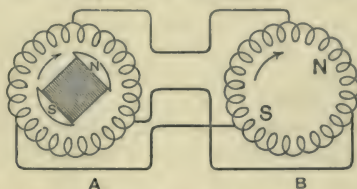


FIG. 49.—Rotating fields.

three wires taken to the stationary part or **stator** of a similar machine B. A consideration of the directions of the currents at any time will show a reversibility of the action. Just as the revolving field at A produces currents with a certain phase relation to one another, this combination of currents produces a revolving field in B. A field-magnet like that at A, if placed in the field at B will revolve with the same speed as A. In fact an alternator can reverse its action and act as a motor.

Motors of this kind are sometimes used and are called **synchronous motors**, but they have the disadvantage that they have to be excited separately by a continuous current and can only run at one speed. If, however, we place in the stator B, a rotating part or **rotor** containing closed conducting circuits not connected to the supply in

any way, currents will be induced in these, exactly as if they formed the secondary of a transformer; and as in the case of the simple A.C. electro-magnet, forces will be exerted which will cause the rotor to follow the rotating field, although it is unable quite to keep up with it, the difference between its speed and that of the rotating field being called the **slip**. A motor of this sort is simpler and more convenient than a synchronous motor and is called an **induction** motor.

In some induction motors a form of rotor called a **squirrel-cage rotor** is used consisting simply of copper bars laid in slots in the laminated core, and connected together by rings at the ends. In other machines coils of wire are used, and they are sometimes connected to slip rings to enable resistances to be put into the rotor circuit at starting. A certain amount of speed regulation can also be obtained in this way, because the introduction of resistance in the rotor circuit increases the slip and lowers the speed. For the sake of simplicity, a two-pole arrangement is shown in Fig. 49, but the action would, of course be the same in a multipolar machine. A procession of North and South poles would follow one another round.

There are other types of alternating current motors constructed with commutators which are principally used for single-phase working. A motor built on the lines of an ordinary continuous current motor, if made with laminated field-magnets as well as a laminated armature, will run on an alternating current circuit.

Conversion of A.C. into D.C.—It is sometimes required to produce continuous currents where only an alternating current is available. For this purpose a machine called a **rotary converter** is used which is simply a dynamo with both a commutator and slip-rings connected to its armature. The alternating current is fed into the slip-rings and the continuous current is taken out from the commutator so that the machine acts as a combined synchronous motor and continuous current dynamo. A rotary converter can also be used for converting continuous current into alternating current.

An example of the use of alternating current and continuous current, including the employment of alternators, transformers and rotary converters is presented by the London Underground Railways. Three-phase current at 11,000 volts, 33 cycles, is generated by a group of alternators driven by steam turbines at the large station at Lots Road, Chelsea, and is passed through cables to a number of substations in various parts of London, where it is transformed down by transformers to a voltage suitable for the rotary converters which convert it into continuous current at about 600 volts. It is taken at this pressure by another set of cables to the rails from which the collectors on the trains pick up the current. The motors which drive the trains are of the ordinary continuous current type.

CHAPTER X.

SOME ELECTRICAL MEASUREMENTS.

Direct Measurement of Currents and Voltages.—It has already been seen that the heating, magnetic and chemical effects of currents can be used as means of measuring them, and reference has been made to one or two types of **ammeters**, in which the strength of a current is read direct in amperes; and of **voltmeters**, in which the difference of potential between two points is measured by reading the small current produced when a high resistance is connected between them. An ammeter is essentially a low resistance instrument, for its resistance should not add appreciably to the total resistance of the circuit with which it is in series; while a voltmeter is essentially a high resistance instrument as its resistance should not alter appreciably the potential difference across that portion of the circuit with which it is in parallel.

Shunts and Series Resistances.—With the types of instrument most commonly in use, it is only in the case of very small currents that it is usual to pass the whole current through the instrument itself. The arrangement adopted is to connect a low resistance or *shunt*, capable of carrying the current to be measured, in parallel with the instrument, as in Fig. 50. Then the current divides in the inverse ratio of the resistances of the shunt and the instrument, and a definite fraction passes through the latter. Care has to be taken that the shunt is of a material the resistance of which is not much affected by temperature. It is thus possible to use one and the same instrument for a great variety of ranges by providing a number

of shunts of different sizes. This is particularly convenient in the case of portable testing instruments.

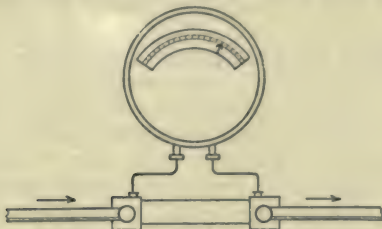


FIG. 50.—Ammeter with shunt.

In like manner a voltmeter is seldom made with the actual working part of sufficiently high resistance to be connected directly to the voltage to be measured. An additional high resistance is usually connected in series with it and this can be placed either inside the case of the instrument or arranged separately. Here again a single instrument can be used for several ranges by the provision of a number of alternative resistances or **voltage multipliers**, or by a number of tappings on one resistance. The same instrument can be arranged to measure either current or voltage, becoming an ammeter when connected in parallel with a shunt or a voltmeter when in series with a high resistance.

The values of the resistances required for shunts and series resistances can be calculated by simple applications of Ohm's law.

Wattmeters.—Instruments can also be constructed to read directly the power in a circuit in watts. In one form a moving coil is used, similar to that used in the ammeters and voltmeters just considered. This carries a small current proportional to the voltage of the circuit, but the magnetic field in which it moves is provided by a coil carrying the main current instead of by a permanent magnet. The force deflecting the moving coil is determined by the product of the current and the voltage, that is by the watts flowing in the circuit. Such an instrument can

be used equally well with continuous or with alternating currents, and in the latter case it takes into account the power-factor and automatically reads the true power in the circuit.

Measurement of Resistance.—Resistances are usually measured in practice by comparison with standard resistances. The very simplest method is to pass a current through the resistance to be measured, giving a convenient deflection on a galvanometer and then to substitute for the unknown resistance a series of known resistances until one is found that will give exactly the same deflection on the galvanometer, when the same E.M.F. is applied. A more practical method than this **method of substitution** consists in balancing unknown and known resistances against each other by an arrangement known as the **Wheatstone's Bridge**.

The principle of this piece of apparatus is shown in Fig. 51. The current divides into two paths ACB and ADB

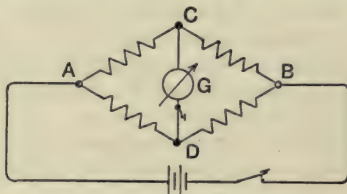


FIG. 51.—Wheatstone's Bridge.

and an intermediate point on each side is connected to a sensitive galvanometer, G. No matter whether the total resistance of ADB is equal to that of ACB or not, some point on ACD can always be found to correspond to any intermediate point C on ACB, where the potential drop along CB and BD are the same and consequently no current flows in the galvanometer. This will be the case when $\frac{CB}{AC} = \frac{BD}{AD}$.

It is easy, therefore, by making the arm AC of an adjustable resistance and the arms AD and DB of resistances of known ratio, to determine the resistance of CB by adjusting AC till there is no deflection in the galvanometer.

Another, and more usual, arrangement is to have a fixed ratio between AC and AD and to adjust DB. The bridge can be made up by arranging the necessary resistances for the arms AC, AD, and BD in the form of resistance coils in a box so that they can be put into circuit as required, by withdrawing plugs which normally short circuit them. The keys controlling the battery and galvanometer circuits respectively are mounted in the same box. In a simpler form of bridge, a slide wire is used for the branch ADB, and the contact D is moved about till a balance is arrived at. It is not even necessary to know the actual resistance of the slide wire, so long as it is of uniform material and section and the resistance AC is known, as it is the ratio of AD to BD that determines the result.

Another method, applied more particularly to low resistances such as those of armature coils in dynamos, etc., consists in passing the same current through the unknown resistance and a known resistance in series with it and comparing the potential drops produced, by a delicate galvanometer.

The Potentiometer.—Another very convenient system of electric measurement depending upon the use of a slide wire and used for the determination of E.M.F.'s and potential differences is that known as the **Potentiometer**.

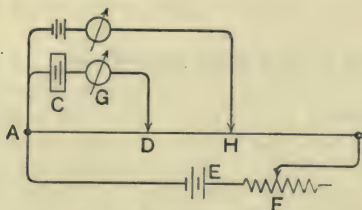


FIG. 52.—Potentiometer.

In this instrument the unknown E.M.F. is compared with that of a **standard cell** the E.M.F. of which is accurately known. The standard cell C (Fig. 52) in series with a delicate galvanometer is connected to the end A of the slide wire, and to the slider D which is set at a point on

the potentiometer wire, where the scale reading corresponds exactly with the known E.M.F. of the cell, which we will suppose is 1.4 volts.

A current is passed along the wire from an independent driving battery E, and is adjusted by means of the rheostat F until no deflection is produced in the galvanometer G. It is then known that the drop of potential due to the current of the driving battery along the section AD of the potentiometer wire is exactly 1.4 volts, as it balances that of the standard cell. The standard cell is then disconnected, but the current in the wire is kept constant so that the voltage drop along it corresponds exactly to the scale readings.

The unknown E.M.F. then replaces the standard cell and a fresh position of balance is found by moving the slider; the value of the E.M.F. to be determined can then be read off directly from the scale. The potentiometer can be used in this way to determine the drop of potential across a shunt carrying a current of any value, and thus to determine a current; or it can measure the voltage across any known fraction of a multiplying resistance to which a voltage too great for direct measurement is applied.

The accuracy of the potentiometer system depends upon the constancy of the E.M.F. of the standard cell, but with pure chemicals, and by taking certain precautions, standard cells of sufficient constancy for the purpose can be made.

Measurement of Very High Resistances.—It is sometimes required to measure high resistances which may even amount to millions of ohms, for which the ordinary Wheatstone's bridge method would not give accurate results. This is particularly so in the testing of the perfection of insulation; for, as we have seen, no insulating material is of really infinite resistance and a minute leakage current always passes where an E.M.F. is present. The question becomes of importance in the testing of the insulation of the windings of electrical machinery, etc., and in ascertaining the condition of the wiring of an electric light installation before it is allowed to be connected up to the mains. This is done by measuring in millions of ohms

or **megohms**, as they are called, the **insulation resistance** between the two poles with the circuit open, that is with all the switches off, and between either pole and the earth. It is upon the high value of these that freedom from leakage of current depends.

The simplest method is to employ a battery of fairly high voltage and measure directly the minute current produced by means of a delicate galvanometer, but special instruments of what is known as the **ohmmeter** class are also made, in which the ratio of the voltage applied to the current produced is indicated on a scale, so that the insulation resistance in megohms can be read off if the scale is suitably graduated. In one form of this, the amperes pass through a fixed coil and the current proportional to the voltage passes through another at right angles to it and a pivoted needle takes up a position in the resultant field which corresponds to the ratio of the volts to the amperes.

In another pattern two moving coils, on one frame at right angles to each other, are used and move in the field of a permanent magnet. The testing voltage may be as high as 500 volts and is provided by a small hand-driven magneto-generator.

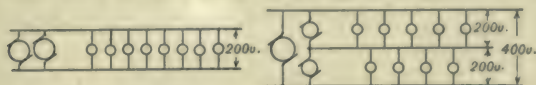
CHAPTER XI.

ELECTRIC LIGHTING AND HEATING.

Current Supply for Electric Lighting.—Primary batteries are only used for the supply of current to very small lamps, such as pocket lamps and hand torches. Electric lighting on motor cars is carried out by accumulator batteries, and these are often charged by small dynamos driven by the engines of the cars. Isolated installations of moderate size, such as those in country houses, are usually supplied by a dynamo driven by a petrol, oil or gas engine, and an accumulator battery is generally provided so that the light is always available, although the engine is only run at convenient periods. Most electric lighting is supplied from the public **electric supply mains** which derive their current from large **generating stations** where dynamos are always kept running, driven by steam turbines or engines, or by gas or oil engines or, in districts where it is available, by water power.

In some of the smaller stations, continuous current plant supplies current directly to a **distributing network** of mains, which may consist either of overhead wires or, as is more usual in this country, of underground cables. In what is known as the **three-wire system** of distribution, often employed with stations of this kind, instead of only two conductors being used, for the outgoing lead and the return respectively, as at **A** in Fig. 53, a third or **neutral** main is used as well as the **positive and negative** mains, as shown at **B** in the same figure. Some of the lamps are arranged on one side of the circuit and some on the other. The dynamos in the station are arranged so as to keep the voltage balanced so that it is always equal on both sides.

A three-wire system of this kind conduces to economy in copper in the mains, as the middle wire has only to carry the difference in the loads or the **out of balance current**.



A. Two wire system

B. Three wire system

FIG. 53.—Distribution systems.

A usual distributing voltage is 200 or 220 volts, but some of the older stations were equipped with 100 volt plant. Other stations contain only alternators, and in this case a voltage of some thousands of volts is used and this pressure is stepped down to one of the usual distributing voltages by transformers, either on the consumers' premises or in substations, which feed a low tension distributing network. In other large schemes alternating current transmission is employed in conjunction with continuous current distribution. (See page 69.)

Circuit Breaker.—There are many points of interest in the generation, transmission and distribution of electric currents on a large scale which cannot be gone into here; such as the arrangement of the switchgear for controlling the output of the station, and the protective devices employed for preventing excessive currents from flowing on the occurrence of short-circuit, due to accidental contact between parts of the circuit of opposite polarity. This is done by **circuit breakers** which automatically disconnect any portions of the circuit which may have become faulty, before the short-circuit current has had time to do damage.

The simplest arrangement of this kind is the ordinary **fuse**. This is a short piece of an easily fusible metal such as tin, which melts and breaks the circuit immediately a current much in excess of the normal working current begins to flow. Ordinary house wiring, for example, consists of a number of branch circuits each provided with a fuse on each pole arranged on a distribution board at the point where these circuits branch off from the main conductors.

Incandescent Lamps.—Most electric lighting is carried out by **incandescent electric lamps**, in which a thin **filament**

of a durable material, enclosed in a glass bulb with suitable provision for leading the current in and out, is heated to a white heat by the passage of an electric current.

A great deal of experimenting had to be done before a suitable material was found. For some time, the material which had proved the most satisfactory was carbon, which can be made into thin filaments of sufficient durability and of suitable resistance by a special process. This consists in squirting an organic chemical preparation known as cellulose through a very small hole in a die, and afterwards heating the thread so formed, to drive off all other constituents than the carbon. The hard black almost metallic filament thus produced is mounted on the leading in wires and is sealed into a glass bulb, which has to be very completely exhausted of its air to prevent the carbon burning away.

Such carbon filament lamps, if overheated, are liable to drive off from the filament carbon particles which quickly blacken the glass, and the filament soon disintegrates or falls to pieces. Satisfactory results are attained if the filament is heated to such a temperature that the light given out amounts to one candle-power for every $3\frac{1}{2}$ to 4 watts consumed. Thus a 16 c.p. **carbon filament lamp** takes about 60 watts. These lamps have been made with thick filaments for low voltages and with thin filaments for high voltages, throughout a very considerable range of candle-power, but in all cases the consumption in watts per candle-power or, as it is sometimes called, the efficiency, is about the same.¹

Metal Filament Lamps.—It was afterwards found that various comparatively rare metals of very high melting points could be made up into filaments which could be

¹ The efficiency of an incandescent lamp is not very suitably expressed in watts per c.p. because this figure decreases as the efficiency of the lamp improves. Again to speak of a lamp as of so many candle-power is rather vague as the c.p. varies very much in different directions. In practice, c.p. is specified either in a particular direction, as a mean in the horizontal plane, as a mean over the lower hemisphere or over the whole sphere. The figures in this chapter refer to mean horizontal candle-powers for an upright lamp.

heated to much higher temperatures than carbon, without destruction, and without blackening of the bulb. Osmium and tantalum were used to some extent, but even better results were obtained with tungsten, which is the material of which the filaments of all present day incandescent lamps are made. Tungsten filaments have to be a good deal longer and thinner than carbon filaments for the same conditions, and some difficulty was experienced at first in making them in small sizes for high voltages. The early tungsten filaments were made by a squirting process from metallic tungsten powder with a binding material and were afterwards heated to consolidate the filament, and to expel the binder, but methods of drawing true tungsten wires of sufficiently small diameter have since been perfected.

The higher the temperature to which a body is heated the greater is the proportion of visual light rays emitted, and the whiter is the light produced. Consequently the higher temperatures at which the metal filament can be run result in a considerable gain in efficiency over the carbon filament. In this class of lamp a figure as high as 1 watt per candle-power may be attained.

Certain differences in the behaviour of carbon and metal filament lamps are due to the resistance of carbon decreasing and the resistance of metals increasing with rise in temperature. The fact that a carbon filament has a higher resistance cold than hot causes it to light up perceptibly slower than a metal filament lamp, when both are switched on together, as the current has to build up gradually while the filament heats up and lowers its resistance. In the metal filament, on the other hand, the initial current may be momentarily higher than its final value owing to the lower resistance of the material when cold. For the same reason, the light given out by a metal filament lamp is much less affected by variations of voltage.

The next advance in efficiency was due to the discovery that a tightly coiled up tungsten wire filament can be run at a still higher temperature without failure, if the bulb, instead of being exhausted to a vacuum, contains a gas of an inert character. Nitrogen was first used, but some of the lamps now made are filled with rare gases

such as argon. By this means, the efficiency of the large sizes of lamps could be raised as high as 0.5 watt per candle-power, and for this reason they were at first known as **half-watt lamps**. These lamps are now made in small as well as large sizes, but the efficiency of the small sizes, although much better than that of the metallic filament vacuum lamp, is not quite as good as half a watt per c.p. Hence it is better to speak of them as **gas-filled lamps**.

Nernst Lamps.—One of the attempts to produce an incandescent lamp of better efficiency than that possessed by the carbon filament lamp, depended on the use of a material which is practically a non-conductor at ordinary temperatures but becomes conducting when hot, and is sufficiently refractory to be raised to a very high temperature without the necessity of keeping it from the air. In the Nernst lamp, a short thick filament composed of an oxide of one of the metals of what is known as the "alkaline earth" group, such as zirconium, thorium or cerium or a mixture of such oxides, is arranged to be heated by a little wire coil through which a current is passed. The filament is in parallel with this auxiliary heating circuit, and as soon as it is raised to a sufficiently high temperature to become conducting, a current passes which causes it to be raised to a still higher temperature and to glow with a brilliant white light. The heating coil, being no longer required, is automatically cut out of circuit by an electromagnetic device.

The Electric Arc.—An entirely different way of producing light from an electric current is by means of what is known as the **electric arc**. It was found many years ago, that if the wires from a battery of a considerable number of cells were connected to two rods or pencils of carbon, and after establishing the current by touching them together the carbons were drawn apart a little way, the current was not interrupted, but continued to flow across the intervening space, forming an intensely hot flame or **arc** and causing the points of the carbon rods to glow with a brilliant whiteness. If the carbons were separated too far, the arc went out and the electrodes had

to be brought together and separated again to re-establish the arc. This is the principle made use of in the **arc lamp**, which before the days of the incandescent lamp formed the sole available form of electric light. Arc lamps are still used to some extent for lighting large interiors or open spaces and in lighthouses, searchlight projectors, cinematograph lanterns, etc.

The current may be said to be conducted across the arc by carbon in a sort of gaseous form or vapour of high resistance and several effects worthy of notice are produced. The carbons gradually burn away, but it is found that the positive carbon is consumed about twice as fast as the negative, and that the points of the two burn to a different shape as shown in Fig. 54. The negative remains pointed and the positive forms what is called a **crater**. Particles of carbon appear to be carried across the arc from the positive to the negative pole, hollowing the crater and sharpening the negative tip. The true explanation of the action is however a little more obscure. The greater part of the light (about 85 per cent.) comes from the hot surface of the crater, which is at a temperature of about 3000°C . A limited amount of light (about 10 per cent.) also comes from the tip of the negative carbon, but with ordinary carbons the glowing gases in the arc itself do not contribute much (about 5 per cent.) to the total lighting effect. On account of the difference in their rates of burning away, and also to avoid the negative carbon getting in the way of the crater more than is necessary, the negative carbon is made of much smaller diameter than the positive. The maximum illumination is in the direction of the arrow in Fig. 54.

An arc can be formed only if the voltage between the electrodes exceeds a certain definite amount in the neigh-



FIG. 54.—The electric arc.

bourhood of 40 volts. The actual ohmic resistance of the carbon vapour of the arc varies with its length and cross-section, but the behaviour of the arc is not simply like that of a resistance, for the equivalent of a back E.M.F., such as was met with in the consideration of electrolysis, is produced at the surface of the crater. It is possible to form an arc with other materials than carbon; between certain metals, for example, or between carbon and a metal; but for most practical purposes carbon arcs are used.

Arc Lamps.—In an arc lamp, it is necessary for mechanism to be provided, whereby the carbons can be brought together and separated to **strike the arc**, as well as to feed them together as they burn away. These actions can be performed by hand through suitable gearing, as is sometimes done in stage lamps and other projectors, or by an automatic arrangement actuated by solenoids or other electromagnetic devices. The voltage, current and length of arc have to be adjusted very carefully, or there may be too rapid a volatilisation of the carbon, and an unsteady arc accompanied by a hissing sound will be produced. In some lamps the position and shape of the arc are controlled by the action of a magnetic field which exerts force on the body of vapour exactly as if it were a flexible conductor carrying a current.

Various methods have been adopted to improve upon the characteristics of the ordinary open carbon arc. In **enclosed arc lamps**, the arc is surrounded by a globe which prevents access of fresh air and renders the burning away of the carbons much slower, besides increasing the allowable length of the arc and improving the colour of the light. In **flame arc lamps**, chemical substances are added to the electrodes which greatly increase the luminosity of the arc itself and modify its colour according to the chemical used. In the **magnetite arc lamp**, one electrode is of copper kept relatively cool, while the other is composed of certain oxides of iron and other metals, which yield the luminous arc. For purposes where a very small point of light is required, a lamp in which an arc is produced between tungsten electrodes enclosed in a glass bulb is sometimes used.

Alternating Current Arcs.—So far, only the production of an arc by a continuous current has been considered, but it is also possible to maintain an arc by means of an alternating current. The arc does not cease after the first wave of current, but is established again by the succeeding wave in the opposite direction. Each carbon acts alternately as the positive and the negative electrode, and both develop a certain amount of crater, but it is not so well marked as in a continuous current arc, and both burn away at the same rate. Also the virtual back E.M.F. is not so high as the back E.M.F. of a continuous current arc. The light from an alternating current arc is not really continuous, but flickers in time with the alternations of the current. With ordinary frequencies, this fluctuation is too rapid to be appreciated by the eye, but its effect can be seen by moving the hand with one finger extended, when the appearance is that of several fingers as the succeeding flashes of light illuminate it in different positions. An alternating arc is also liable to be noisy, as when at all out of adjustment, it gives out a loud humming noise, the note of which corresponds to the frequency of the current.

Mercury Vapour and Vacuum Tube Lamps.—Other forms of electric lamp depend upon a current passing through a conducting vapour or gas at a low pressure in a tube. In the **mercury vapour lamp**, which is really an arc lamp in principle, an exhausted tube contains some mercury arranged so that when the tube is tilted, a little column of mercury flows along it and establishes connection between the masses of mercury at the ends. Tilting the tube back again breaks the circuit and establishes a long arc through the mercury vapour which the tube contains, causing it to glow with a greenish coloured light rich in the actinic rays required for photography. Only a very moderate amount of heat is developed. Other vacuum tube lamps containing small quantities of the rare gases such as **neon** are also sometimes used, but their action depends on a somewhat different principle.

Electric Heating.—In addition to providing an intense source of light in arc lamps, the extremely high tempera-

tures attainable in the electric arc are utilised on a large scale in electric **arc furnaces**, for the preparation of steel, aluminium and other metals and for the manufacture of various chemical substances, including calcium carbide (used in the production of acetylene), carborundum and certain fertilisers. The electrodes consist of large carbon blocks and currents as high as 20,000 amperes are employed.

Another industrial use to which the electric arc is put is the production of nitrogen compounds (of importance in peace time for the purpose of agricultural fertilisers and in war time for the manufacture of explosives) by causing the nitrogen and oxygen of the air to combine in the flame of the arc. Arcs working at pressures up to 5000 or 6000 volts are used for this purpose.

A different form of electric furnace, which is worked with alternating current, employs the principle of the transformer. Powerful currents are induced in the mass of the material to be heated, which acts as the closed secondary. This kind of furnace is called the **induction furnace**. As already briefly stated in Chapter II., most cases of electric heating, including heating rooms, cooking, etc., are examples of heating by the resistance method. For a large variety of heating appliances, the **heating element** is composed of wires of a special alloy of nickel and chromium, which is not liable to corrode away at high temperatures. Small **resistance furnaces** are used for various industrial and experimental purposes, and a form of electric furnace is used for tool-hardening and similar work, in which the conductor consists of a bath of a molten salt, which is conducting when hot but not when cold. In some forms of electric boiler the current is actually passed through the water itself. In this case, alternating current must be used to avoid electrolysis.

Where very localised heat is required, as in **electric welding**, either the arc or the resistance method can be employed. In the latter case, powerful currents are passed through the metals at the point of the weld by suitable contact jaws which press them together.

CHAPTER XII.

TELEGRAPHY AND TELEPHONY.

General Principles of Telegraphy.—The magnetic effect of an electric current furnishes a ready means of sending messages from one place to another. All that is required is a galvanometer or its equivalent, at one end of the line, and a battery at the other end with a key or other device for making and breaking the current according to the well-known **Morse code**. Either a reversing arrangement can be used to give momentary current impulses, sometimes in one direction and sometimes in the other, or a simple key to send long or short current impulses, or as they are generally called, dots and dashes. A simple arrangement is shown in Fig. 55. A reversing key is shown at A, which

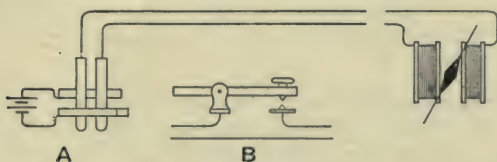


FIG. 55.—Simple telegraph system.

will give currents in different directions according to which finger is depressed to make contact with the positive pole of the battery, while the other is left up in contact with the negative pole, and a **Morse key** for sending dots and dashes by momentary or prolonged pressure on the knob is shown at B.

Earth Return Circuits.—In practice, instead of two line wires being employed, as in Fig. 56, the current is usually allowed to return through the earth, by burying metal earth plates at each end, as it is found that the earth behaves like a conductor of very low resistance. The

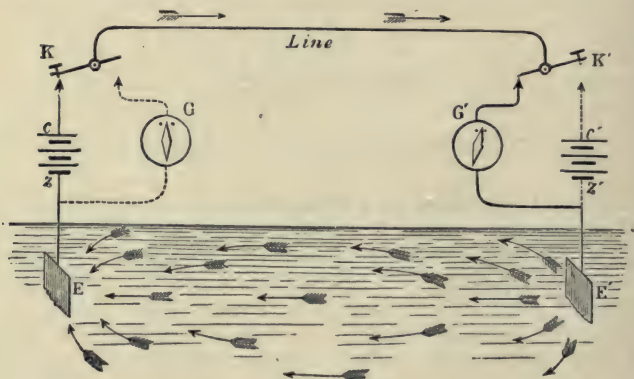


FIG. 56.—Earth return circuit.

circuit shown in Fig. 56 works in this way, and is also arranged for sending and receiving from either end by the provision of a back contact on the key which keeps the galvanometer circuit closed when a current is not being sent. Neither end, however, can send and receive at the same time.

Receiving Instruments.—There are a number of ways in which the signals may be received. The simple system with a reversing key and a vertical galvanometer is still sometimes used and is known as the **single needle system**. The dots and dashes sent by a Morse key can be received audibly by a **Morse sounder**, in which an electro-magnet attracts an armature with a loud click, while another click is produced when it is released, and the operator relies entirely on hearing the signals. In the **Morse ink-writer** an extension of the armature carries a little inky wheel which presses against a paper strip kept moving by clock-

work, and as long as the armature is held down, and thus actually marks the dots and dashes in ink on the moving paper strip.

Some of these instruments require rather stronger currents to work them than can conveniently be passed through a long line. In this case, a **relay** is employed in which an electro-magnet with a very large number of turns of wire, so that it can respond to a weak current, attracts a light armature provided with a contact arrangement to make and break circuit of a local battery, giving a current strong enough to do the work required. Various other methods of reception are used. In some, involving more or less complicated mechanism, but all depending on the attractions exerted by electro-magnets, the received message is actually printed in type automatically.

Automatic Sending.—The signalling speed in words per minute that can be maintained in all these arrangements is limited by the rate at which the keys can be worked by hand. When long messages are required to be sent quickly, as for newspaper work, the **Wheatstone automatic** system is used. In this system, a special apparatus is used to punch holes in a paper strip corresponding to the Morse signals for each letter, and the strip is then passed through an apparatus, whereby a contact is made every time a hole in the paper passes, and a signal current is sent into the line. Speeds up to 100 words per minute can thus be maintained, and one transmitter can keep a number of perforators busy, if it is to be supplied at its full capacity.

Methods of Sending more than one Message at once over one Line.—When it is required to send two messages over the same line in different directions simultaneously, some form of **duplex system** is used, in which arrangements are made so that each sending key affects the distant receiver but not its own. In the **differential duplex** system (Fig. 57), each receiving instrument has two coils connected in such a way that depressing the key at one end sends the line current through one coil of its own receiver and a current in the opposite direction, on the other coil. This

is adjusted by means of a resistance to be exactly equal to the line current, so that no effect on the home instrument is produced. The current, however, passes through the



FIG. 57.—Differential duplex system.

coils of the distant instrument in the same direction, as will be seen by following out the course of the current in Fig. 57.

In the **bridge duplex system** (Fig. 58), an arrangement like the Wheatstone's bridge is employed at either end,

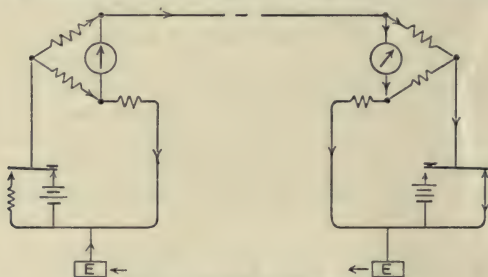


FIG. 58.—Bridge duplex system.

with the receiving instrument in the place occupied by the galvanometer in the ordinary form of bridge for testing purposes, and the resistances of the arms are adjusted so that no current flows through the home instrument when the key is depressed, although part of the line current flows through the instrument at the distant end.

For sending two messages at once through a line, in the same direction, an arrangement called the **duplex**

system is employed. Two sets of receiving relays are used one of which consists of **polarised relays**, *i.e.* relays with permanently magnetised armatures, which respond only to currents in one direction; while the other relays have springs holding back the armatures, so that they are only actuated by currents above a certain value. One set of keys is arranged to reverse the current and the other to alter its strength in accordance with the signals. The diplex system can be combined with the duplex to form the **quadruplex system** in which four messages, two in each direction, can be sent simultaneously over a single line. A still larger number of signals can be sent together by the **multiplex system**, one form of which depends upon the use of rapidly revolving contact arms at the two stations, driven at exactly the same speed and in step with each other, whereby successive contact is made with a number of local circuits.

Transmission of Handwriting.—An ingenious instrument called the **telaugraph** has been devised by which messages are actually received in the hand-writing of the sender; or even simple sketches can be drawn at both ends of the line at once by an artist. The movement of the sending pencil in an up and down direction regulates the current in one circuit by cutting resistances in and out, and its movement backward and forwards in a sideways direction similarly regulates the current in another circuit. The two components of the movement of the pencil are recombined at the distant end by two moving coil galvanometers, which control the movement of the receiving pen in vertical and horizontal directions respectively, according to the strength of the currents in the two circuits. The apparatus requires two line wires for its working, even if earth return circuits are used.

Telegraphic Transmission of Photographs.—Many attempts have been made from time to time, with varying degrees of success, to transmit photographs or drawings electrically. A copy of the picture to be sent is mounted on a revolving drum which is given an axial feed, and a similar revolving drum at the distant station carries the

photographic film for its reception. Arrangements are made so that whenever a dark part of the picture passes a certain point, a current is sent or interrupted in the line which controls a beam of light falling on a corresponding point on the receiving film. Sometimes this is done by taking advantage of the property of selenium of changing its resistance under the action of light, and sometimes the original copy of the picture is in the form of a metal relief in which the lines or dark parts stand out and make contact with a stylus as the drum revolves. Again, a number of different arrangements have been proposed for effecting the control of the beam falling on the receiving film.

Submarine cable telegraphy.—In communicating across intervening seas by **cables** laid in the bed of the ocean, the same general principles are employed, but very much more sensitive apparatus must be made use of, and certain difficulties are introduced owing to what is called the capacity of the cables causing the current impulses forming the signals to take an appreciable time to grow to their full value and to die out. The cause of this effect will be made clearer later, when we come to a further consideration of this property of capacity. The actual cables consist of a core of copper wires covered with gutta-percha, provided with a protecting sheath of a fibrous material such as jute impregnated with a bituminous compound and armoured in some cases with steel wires.

The Telephone.—The transmission of actual speech, which is accomplished by the **telephone**, has many advantages over the best systems of telegraphy. The very simplest form of telephone is the toy in which two tightly stretched membranes or **diaphragms** held in suitable cups are joined by a string fastened to the centre of each diaphragm. When the sound waves of the voice (and sound is nothing but the movement of the air in more or less regular waves) fall upon the diaphragm, they cause it to vibrate. If the string is held tight, the diaphragm at the far end is given exactly the same series of movements and imparts vibrations to the air in its cup which

faithfully copy those due to the original voice. Such an apparatus will only work over very short distances, but by electrical means we can make the vibrations of the diaphragm in the transmitter produce fluctuations of current in a line of almost any length which will cause the diaphragm of the receiver to follow the movement of the transmitting diaphragm as truly as if they were joined together by a string.

The Transmitter.—In present-day telephones, this is done in the following way. The diaphragm *D* of the transmitter (Fig. 59) has behind it a little box, *EE*, filled with carbon granules loosely packed between flat electrodes attached to the diaphragm and to the back of the case respectively. The movement of the centre of the diaphragm backwards and forwards, as it vibrates in sympathy with the sounds spoken into the mouthpiece *M*, causes a variation of the pressure and a consequent tightening and loosening of the granulated carbon. This alters the resistance of the whole mass which is included in the line circuit and thus produces pulsations in the line current corresponding to the original sound waves. This form of transmitter is called a **microphone**.

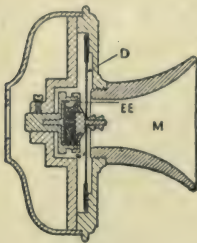


FIG. 59.—Microphone transmitter.

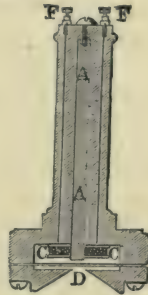


FIG. 60.—Bell receiver.

The Receiver.—In the receiving instrument (Fig. 60), which is still practically of the original form as invented by Graham Bell in 1876, this fluctuating current is brought in through the terminals, *FF*, and passes through the coil, *C*,

wound round one pole of the permanent magnet AA. The fluctuations in the current cause variations of the pull of this magnet on the sheet iron diaphragm D, which is close to one pole. The diaphragm of the receiver is thus caused to vibrate and to copy the movements of the diaphragm of the transmitter exactly as in the simple string telephone. In some of the more modern forms of the **Bell Receiver**, a bent-up magnet with both its poles near the diaphragm and provided with a coil on each pole, is used to obtain greater power.

Reversibility of the Bell Receiver.—It is interesting to note that the action of the Bell receiver is reversible. Two instruments, each like that shown in Fig. 60, can simply be connected together by wires without any battery at all and speech can be transmitted from one to the other. This is because the movement of the diaphragm in the instrument acting as the transmitter causes variations in the lines of force linking the coil, and thus induces minute fluctuating currents therein, which are sufficient to actuate the other instrument as a receiver in the ordinary way. This was actually done in the original Bell telephones, as the microphone was not developed as a transmitter until a few years later.

The Induction Coil.—In practice, it is only in the case of short lines that the current from the microphone battery passes through the line. Telephone currents depend for their effects on their continual changes in value, and like the more regular alternating currents considered in Chapter IX. can be made to work a transformer, or as telephone engineers more often call it an **induction coil**. By this means, more convenient relations between voltage and current can be obtained. It is also important to note that in this case, the microphone current, put into the primary, is a fluctuating current varying from zero to a maximum value, but always in the same direction, whereas the secondary, or line current taken from the secondary, is truly alternating. This gives a better action in the receiver, as the flux due to the coil sometimes assists and sometimes opposes that due to the permanent magnet,

instead of always being added to it as in the case of direct connection to the microphone.

Telephone Circuits.—For telephones, two line wires are nearly always used, as the earth return system is found less practicable than in telegraphy on account of the greater sensitiveness of the apparatus to stray earth currents from other sources. As in the case of telegraphy, the wires may be overhead, under-ground, or under the sea.

Telephones are used in conjunction with call bells which may be of the ordinary trembler type, worked by batteries, or of an alternating current pattern. The latter are arranged so that the armature is alternately attracted in one direction and the other as the electro-magnet reverses its poles. The low frequency alternating current required is obtained from a small hand-driven **magneto generator**. A typical arrangement of connections for battery bells is shown in Fig. 61, where the change-over from the ringing

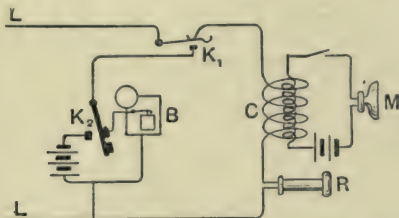


FIG. 61.—Connections of telephone and bell circuits.

circuit to the telephone circuit is made by lifting the receiver off the spring **switch hook** K_1 which is normally held down by the weight of the receiver. The way this is done will be seen by following the circuits in Fig. 61, which also shows the **ringing key** K_2 , which cuts out its own bell and puts the battery across the line to ring the distant bell when pressed. The connections of the microphone **M**, the receiver **R**, and the induction coil **C**, are also shown. The hook can, if required, be made to make and break the microphone circuit.

It is impossible to enter here into the somewhat complicated arrangements employed in **telephone exchanges**, to enable the operator to distinguish which subscriber is calling and to connect his line either with another line from the same exchange through a **junction line** to another exchange in the same area or through **trunk lines** to a distant area. In the earlier exchanges, the call signals were all worked by magneto generators in the subscriber's sets, and each subscriber had his own local microphone battery of a few dry cells, but in the modern **central battery system** a large accumulator battery at the exchange works all the microphones. The call signals, which consist of small lamps on the exchange **switchboard**, are caused to light up by a set of relays when the calling subscriber takes his receiver off its hook, and to be extinguished when he hangs it up again. All the subscriber's bells are rung by current from alternating current generators kept continuously running at the exchange.

In some of the most recent exchanges, the necessity for operators continually watching for signals and making the required connections is dispensed with. In the case of these **automatic exchanges**, a dial switch is set by the calling subscriber in accordance with the successive figures of the number required and the resulting series of current impulses actuates an electro-magnetic selector switch giving automatic connection to the required line.

Telephone engineering is a large subject and many special problems are presented owing to the rapidly fluctuating nature of telephone currents. In the case of long lines, difficulties are caused by attenuation of the current waves to an extent which makes audibility difficult and a certain amount of distortion of the wave form is also produced which interferes with the reception of recognisable speech. Again, it is not such a simple matter to make a relay suitable for telephone currents as it is in the case of telegraphy, although, as will be seen later, this has now been accomplished.

CHAPTER XIII.

STATICAL ELECTRICITY.

Statical Electricity.—In the preceding chapters, effects have been studied which are produced when a circuit is completed between two points having a difference of potential maintained between them by some means, and we have seen that these effects can be turned to many useful purposes. Attention will now be directed briefly to some of the effects which are produced when an E.M.F. is present but the circuit is not closed and no current is passing; that is to say, when the electricity is at rest in a body and not flowing along as a current in a conductor. The effects that we are speaking of require rather higher voltages than those hitherto dealt with, to be readily appreciable. They were discovered long before electric currents were known, and they were originally produced, as will be seen, in quite another way.

Of course, no substance is really an absolutely perfect insulator, so that no circuit is of infinite resistance. The difference is thus really one of degree, as, in one case, we are dealing with the effect of considerable currents propelled by moderate pressures, and in the other, the effect of enormous pressures which are not producing appreciable currents. Electricity under these conditions can produce some effects that we have not yet considered, and is sometimes spoken of as **statical electricity** and the study of its phenomena is called **electrostatics**.

Electric Charge.—Consider the case of a battery of a great number of cells (Fig. 62), the poles of which are connected to two plates A and B, separated by an insulating

medium (or, as it is sometimes called, a **dielectric**) such as dry air. Although no current will flow, the plates are at a high potential difference and may be regarded as containing quantities of electricity of opposite polarity and, provided

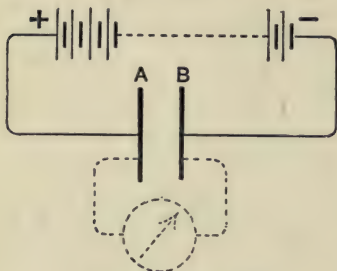


FIG. 62.—Electric charge.

that they are well insulated, they will retain these **positive** and **negative** charges even after the wires to the battery are disconnected. If, while they are so charged, a circuit, such as that shown dotted, be provided, a momentary rush of current is produced while the positive and negative charges neutralise each

other, and a sensitive galvanometer, if included in the circuit, will be temporarily deflected. The plates are then at the same potential and are said to have been **discharged**. The current will not persist, as there is no source of E.M.F. to maintain the supply of electricity.

It is quite immaterial whether we regard the positive and negative charges as quantities of really different kinds of electricity with opposite properties, or consider the one as an excess and the other a deficiency of a single kind of electricity.

Dielectric Strain.—The dielectric between the plates, although not allowing a current to pass, is in a state of strain, electrically speaking. If the plates be brought near together (causing what we may call the **potential gradient** to become very steep) the dielectric may not be able to stand the strain and a discharge may pierce its way through the dielectric in the form of a bright *spark*. Different materials vary in their dielectric strength. A layer of dry air, one millimetre thick, for example, will stand a pressure of over 4000 volts before it will allow a spark to pass under ordinary conditions; while a film of oil of the same thickness requires at least 30,000 volts to puncture it. With the high intermittent voltages produced

by the induction coils mentioned in Chapter VIII., sparks, or **disruptive discharges**, of great length can be produced. The nature of these sparks will be more fully dealt with in a later chapter.

Electrostatic Attraction.—Electric charges can be made to reveal their presence in other ways than by allowing them to discharge through a conductor, or to break down a dielectric by a spark. It is found that bodies charged with the same polarity repel one another, (like similar magnet poles), while unlike charges attract one another. This repulsion is made use of in the **gold leaf electroscope**, in which two pieces of gold leaf joined at one end by a conductor in an insulating support, such as a glass jar, are seen to fly apart when the conductor is charged.

The attraction between oppositely charged bodies is utilised for measuring high voltages in the **electrostatic voltmeter**, one form of which is shown in Fig. 63. Here the moving needle **N**, counter-balanced by the weight **w** connected to one pole, is attracted by the fixed quadrants **Q**, connected to the other pole, and the pointer **P** indicates the voltage on the scale. More delicate instruments for the detection and measurement of differences of potential depending upon electrostatic attraction are made under the name of **electrometers**.

Electric charges also resemble magnet poles in their property of inducing charges of opposite sign in neighbouring bodies, just as opposite poles are induced by magnets in magnetic bodies in their neighbourhood. It is thus necessary to bring the gold leaf electroscope into actual contact with a conductor to ascertain if it is charged; it is sufficient to present the electroscope near to the conductor, when the knob and leaves will receive an **induced charge** and will diverge as before. In like manner two small balls of a light material such as pith, even if hung on insulating threads of silk, will repel

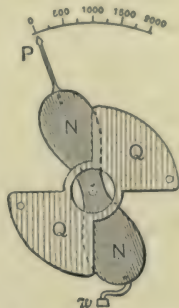


FIG. 63.—Electrostatic voltmeter.

each other when presented to a strongly charged body. Again a charged body will attract any light bodies in its neighbourhood (just as a magnet attracts other pieces of iron whether previously magnetised or not) owing to the charges that are induced in them.

Electrification by Friction.—There are other ways of producing electric charges than by the ordinary current-giving apparatus. One of the simplest is by friction. If, for example, a stick of sealing-wax be rubbed upon the coat sleeve, or better still, by a piece of dry fur, it will be found to have acquired the property of picking up small objects, such as dust and little bits of wood or paper; and if presented to a gold leaf electroscope, will cause the leaves to diverge, because it has become possessed of an electric charge, or as it is sometimes called is **electrified**. The same effect is produced by a dry glass rod rubbed with a silk cloth and it will be found that the silk shows evidences of electrification as well as the glass. Investigation will show that the glass acquires a positive charge, but that of the silk is negative. In the case of the sealing wax, on the other hand, the charge acquired by the stick is negative, while that of the rubber is positive.

In general, when unlike bodies are rubbed together, one takes a positive and the other a negative charge; and all substances could be arranged in a list so that any one produces positive electricity in itself when rubbed against another lower down in the list. Materials of a vitreous nature, such as glass, would come at the positive end of the list, and resinous materials such as sealing wax at the negative end. Hence positive electricity was at one time spoken of as **vitreous electricity**, and negative electricity as **resinous electricity**. The first substance in which this property was observed was amber, which was noticed by the ancient Greeks to possess the power of attracting small objects after being rubbed, and it is to the Greek name ἤλεκτρον (elektron) that we owe the modern word electricity.

Another way of readily producing electrical effects is by drawing a piece of carefully dried brown paper sharply between the tightly closed knees or under the arm, when quite long sparks may be obtained by pre-

senting the finger or any other conductor to the paper.¹ A vulcanite comb passed through the hair becomes appreciably electrified and is seen to attract individual hairs. For long it was thought that only insulating bodies could produce electrification in this way, but even a brass rod will become charged when rubbed, if it be held in an insulating handle to prevent the charge leaking away. In order to produce large quantities of electricity **frictional electric machines** used to be employed, in which revolving glass cylinders or plates rubbed against silk covered pads, while an insulated metal conductor collected the charge.

Forces in an Electric Field.—The whole subject of the action of the forces between electric charges has been developed on similar lines to those briefly reviewed in Chapter V. in the case of magnetic fields. In the same way we speak of **electric fields** and **electric lines of force**, and similar diagrams of their distribution may be made. The force between two charges is likewise proportional to the product of their magnitudes and inversely proportional to the distance between them, and a system of **Electrostatic Units** has been elaborated for theoretical purposes, based on a unit charge which repels another at a distance of one centimetre with a force equal to one dyne, and bearing a known relation to the **Electromagnetic Units** which have already been dealt with.

Electrification by Influence.—It has been mentioned that a conductor can receive an induced charge owing to the presence near it of a charged body. This is sometimes spoken of as being charged by **influence**. Consider, for example, a body C (Fig. 64) having a positive charge. There is a potential gradient in the dielectric surrounding C, so that the potential at a point A (1) will be greater than the potential at a point B further away. Suppose the space AB (2) to be taken up by an insulated conductor, then the difference of potential between A and B will cause a momentary flow of current from A to B, till the potential

¹ The human body, although of high resistance from the point of view of currents of moderate pressures, behaves as quite a good conductor in the case of the high potentials considered here.

all along the conductor is the same. The end A will then have a deficiency, that is a negative charge, and the end B will have an excess of electricity, or a positive charge.

Suppose the conductor connected to earth, (3) a momentary current will now flow to earth, as the conductor was at a higher potential than the earth. The positive charge at the end B will disappear and a somewhat greater charge than before will be present at A, because electricity has flowed out of the conductor to earth until the conductor possesses such a negative charge that the negative potential

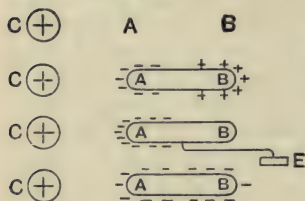


FIG. 64.—Induced charge.

due to it is equal and opposite to the positive potential due to C. The actual potential of AB is now zero. If the earth wire is now disconnected, (4) AB will exhibit the negative charge all over. Thus all that is necessary to charge the insulated top of an electroscope with a positive charge is to present a piece of rubbed sealing wax to it, and to earth the knob by touching it with the finger, or otherwise, before the sealing wax is withdrawn.

Distribution of charge in a Conductor.—It can be shown, by experiments with hollow vessels, that no charge resides upon the inside surface of a hollow conductor, and that the whole of the space inside is at the potential of the conductor. It is only in the case of a spherical conductor that the charge is perfectly evenly distributed over its surface. With other shaped bodies, the sharper the curvature, the greater the density of the charge. The extreme case is that of a pointed conductor, where the density of the charge can become so great that it repels the air sufficiently to cause an **electric wind** sufficient to affect a candle flame.

The Electrophorus.—A method whereby a small charge, produced by friction, may be made to multiply itself almost indefinitely is found in the device known as the **Electrophorus** (devised by Volta as long ago as 1775).

A plate of ebonite, or other resinous material, B mounted on a metal base or sole plate C (Fig. 65) is first given a negative charge by rubbing it with a piece of fur. The metal plate A, with an insulating handle, is then laid thereon, and is momentarily connected to earth with the finger, or otherwise, to get rid of the negative portion of the induced charge. The remaining positive charge will be retained when A is lifted off. The original charge on the ebonite plate is not appreciably diminished as the plate A really only touches B at a few points, so that the effect is practically entirely inductive. The process, therefore, can be repeated again and again. The energy required is provided by the mechanical force to overcome the attraction of the ebonite disc for the plate. The principle can be elaborated further in machines which go through the required cycle of operations mechanically. To the earliest of these, the name of the **continuous electrophorus** was given, but the modern forms are generally known as **influence machines**. By their means, very high potentials and very large charges can be produced.

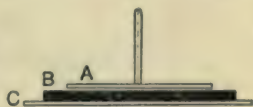


FIG. 65.—The Electrophorus.

The Wimshurst Machine.—One of the best known influence machines is that of **Wimshurst**, the principle of which is shown in Fig. 66. Two glass cylinders are represented rotating in opposite directions. Each carries a number of tinfoil sections which are touched by four metal brushes at certain points as the cylinders revolve. They also pass two collecting combs for the reception of the charges. Suppose one of the outer tinfoil sections starts with a slight positive charge, as it moves to the left in the upper half of the diagram. It will pass one of the inner sections moving past the brush n_1 , which will consequently acquire a negative charge, and carry it on to the right hand collector. On its way, however, it will pass an outer section under the brush n_3 , and will give this section a positive charge so that the process will be continued.

There will thus be a continuous procession of positive charges going to the left collector and a similar procession

of negative charges to the right collector. A similar action is going on in the lower portion. In the actual machines, pairs of plates revolving in opposite directions, side by side, are employed instead of the cylinders which

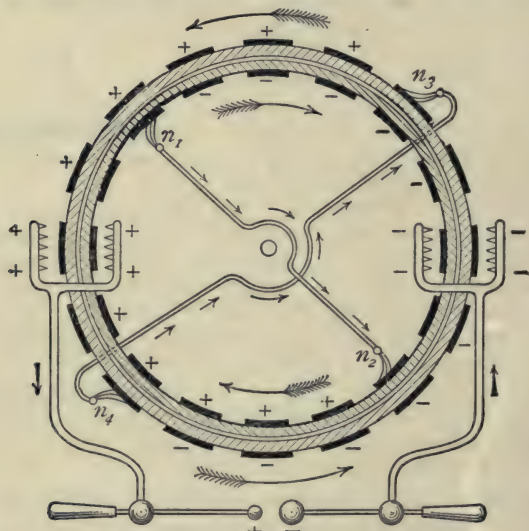


FIG. 66.—Diagram of Wimshurst machine.

are shown in the diagram for greater clearness. It is interesting to note that the action of the Wimshurst machine has been shown to be reversible. The supply of a high difference of potential between the two conductors can cause it to be driven as a motor owing to the electrostatic attractions developed.

Other Methods of Producing Electrification.—In addition to friction, electrification can be produced to some extent by percussion, tearing or cleavage, evaporation, crystallisation, combustion, compression, pressure upon certain crystals and by certain animal actions, as in the case of the **electric eel**, which can give powerful electric shocks to persons or animals touching it.

CHAPTER XIV

CAPACITY AND ITS EFFECTS.

Capacity.—The quantity of electricity present in a conductor as a charge depends not only upon the potential but also upon its size and other conditions. The ratio of the charge in a conductor to the potential producing it is called the **capacity** of the conductor; or in symbols,

$C = \frac{Q}{V}$, where C is the capacity, Q the charge, and V the potential. The capacity in which one volt will produce a charge of one coulomb is called one **farad**. This is, however, rather a large unit for most practical purposes, so a unit equal to one millionth of a farad and called the **microfarad** is more commonly employed. On account of the lack of uniformity in the distribution of the charge in a conductor, it is not always easy to calculate the capacity of a conductor from its dimensions. The simplest case is that of a sphere, in which the capacity (provided that it is at a distance from all other conductors) is proportional to its radius.

Effect of a Neighbouring Conductor.—The capacity of a conductor is very considerably affected by the presence near it of another conductor. Take the case of the two plates represented in Fig. 67. The positive charge on A induces a negative charge on the near side of the plate B and a positive charge on the far side, in the manner already dealt with. The reaction of the positive charge on B upon A almost neutralises that of the negative charge, although the former being nearer has a slight preponderance, so that the potential of A is very slightly lowered

by the presence of the insulated plate B. Consider now the case if B is connected to earth. The positive charge will now be removed and there will be the full difference of potential between the plates. The negative charge has

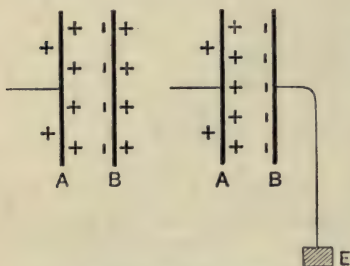


FIG. 67.—The condenser.

now a very considerable effect in lowering the potential of B. As a consequence, a much greater charge has to be sent into A to raise it to the same potential; that is to say, its capacity has been considerably raised. (It amounts to the same thing if, instead of considering B as connected to earth, we consider it

to be connected to the opposite pole of a source of E.M.F. as in the case represented in Fig. 62. In either case it is the difference of potential that we are considering). Such an arrangement is called a **condenser**. The nearer together the plates are, the greater is the increase of capacity produced.

Capacity of a Condenser.—It can be shown that if a sphere of radius a be surrounded by a concentric sphere of radius b , the capacity is increased in the proportion of a to $\frac{ab}{b-a}$. The capacity of a plate condenser with very large parallel plates, which is really the limiting case of concentric spheres, is inversely proportional to the distance between them, provided that the material of the dielectric is not changed. The capacity of a condenser has nothing to do with the material with which the conducting plates, or electrodes, are made; but different dielectrics have different powers of permitting inductive effects through them, or, as it is called, different **specific inductive capacities** or **dielectric constants**. For example, a plate condenser with glass between the plates will have about three times the capacity of an air condenser of the

same dimensions. This property must not be confused with the **dielectric strength** mentioned on p. 96.

The Leyden Jar.—A convenient form of condenser for electrostatic experiments is that known as the **Leyden jar** and shown in Fig. 68. This consists of a glass jar with coatings of tinfoil stuck to the glass, up to a certain height both inside and outside, with a wire terminating in a metal knob communicating with the inner coating. Such a condenser can be charged by connecting the knob to a Wimshurst or other similar machine, while the outer coating is earthed, and if clean and dry, and made of good glass, will retain its charge for a considerable time.



FIG. 68.—Leyden jar.

If a charged jar be held in one hand by the outer coating and the knuckle of the other hand be presented to the knob, a spark will pass between the knob and the knuckle and a powerful shock will be felt as the discharge passes through the body. With a large jar the shock will be strong enough to be dangerous.

A safer way of discharging the jar is, by means of a pair of tongs with an insulating handle. It is usual to connect Leyden jars to the terminals of Wimshurst machines to increase the capacity. By this means much more powerful sparks can be obtained.

Other Forms of Condenser.—The simple plate condenser is not much used except for determining specific inductive capacities of different materials, although groups of plate condensers with tinfoil sheets stuck on to the opposite sides of plates of glass are sometimes arranged in parallel. A form of condenser frequently used for the purposes outlined below is made of sheets of tinfoil separated by paper impregnated with paraffin wax, arranged with alternate sheets connected to either terminal. Mica is

also sometimes used as a dielectric. Variable capacities can be produced by altering the relative positions of sets of interleaved plates in an air condenser. In some cases the capacity is increased by employing compressed air.

Condensers in Series and Parallel.—Condensers, like resistances, can be connected, as already indicated, in parallel, that is with all the positive poles connected together and all the negative poles connected together. The resulting capacity will be the sum of the separate capacities; or in symbols, $C = C_1 + C_2 + C_3 + \dots$. They can also be connected in series, or as it is sometimes called in *cascade*, when the total capacity will be given by the formula $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$. Various methods of measuring and comparing capacities are in use, but cannot be detailed here.

Practical Applications of Condensers.—Condensers form a ready means of absorbing rushes of electricity. When a highly inductive circuit is broken, for example, a considerable rise of voltage takes place at the moment of the break, which is liable to produce a considerable spark. This can be prevented by putting a condenser in parallel with the gap to deflect the discharge, so to speak. The capacity of the condenser will prevent an undue rise of potential and the spark will be prevented. This is done in the case of the induction coil (p. 53), with the result that burning away of the trembler contact is prevented and a much sharper break is produced with a correspondingly higher secondary voltage. Sparking at the contacts of certain telegraph instruments is prevented in the same way. Condensers are also used to a considerable extent in telegraphy for balancing the effect of the capacity of long telegraph lines.

The Effect of Capacity on Alternating Currents.—The effect of applying a continuous voltage to the terminals of a condenser is to cause an initial momentary rush of current, but no subsequent current except a minute leakage current due to the imperfect insulation of the dielectric. The effect of an alternating voltage is very

different, as the condenser is charged and discharged by every voltage wave so that a perceptible current will surge in and out of the condenser, although none can be said to pass through it. As we have already indicated in the chapter on alternating currents, this capacity current is what is called a leading current as it is advanced in phase relatively to the voltage. The capacity of a long cable is sometimes considerable and even upon open circuit a fairly strong current can flow in and out.

When both capacity and inductance are present in a circuit, the expression for impedance includes the capacity reactance as well as the reactance due to self-induction. The current flowing becomes

$$\frac{E}{\sqrt{R^2 + \left(2\pi nL - \frac{I}{2\pi nC}\right)^2}}$$

where C is the capacity in farads (not microfarads).

EXAMPLE.—A pressure of 110 volts at 60 cycles is applied to a condenser of a capacity of $\frac{1}{3}$ microfarad through a resistance of 5 ohms. Omitting the self-induction term, what is the current?

$$\frac{E}{\sqrt{R^2 + \frac{I}{4\pi^2 n^2 C^2}}} = \frac{110}{\sqrt{25 + \frac{I}{4\pi^2 \times 3600 \times (\frac{1}{3} 10^{-6})^2}}},$$

which works out to about 0.013 ampere.

The Effect of Capacity on Telephone Currents.—The still more rapidly varying currents in telephone circuits are capable of surging in and out of condensers in the same way and to such an extent that speech can be maintained as well over a circuit containing a condenser as over one without. This fact is made use of to a considerable extent, particularly in the central battery system, to prevent continuous currents flowing in parts of the circuit provided only for telephone currents.

As already pointed out in Chapter XII., the presence of capacity in long telephone lines has a considerable effect in distorting the wave form of the current and interferes

with the recognisability of speech. One way in which this effect is minimised is by adding self-induction in the form of coils spaced along the line. Such coils are called, after the inventor, **Pupin coils**.

Oscillatory Nature of the Discharge.—So far, the discharge of a Leyden jar or other condenser has been considered as the passage of a single spark transferring the quantity of electricity forming the charge and effecting the discharge practically instantaneously. The action is really a little more complicated. Suppose first that the condenser is discharged through a high resistance with practically no self-induction, the discharge will then consist of a single rush of current which will quickly grow to a maximum and gradually die away. Now suppose that the discharge circuit has low resistance, but considerable self-induction.

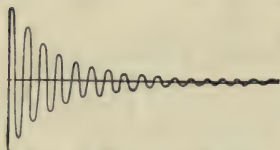


FIG. 69.—Electrical oscillations.

The first rush of the discharge has nothing to restrain it, or throttle it down, as it had with the high resistance, and, being possessed of the equivalent of considerable inertia, owing to the self induction, actually overshoots the mark

and partially charges the condenser in the opposite direction, only for it to discharge again and to take several **oscillations** to and fro before equilibrium is established, as shown in Fig. 69.

This oscillatory nature of the discharge is shown when the spark from a Leyden jar is viewed in a rapidly revolving mirror, when it is seen to consist of several sparks rapidly following one another instead of a single spark. The case is very like the sudden release of a spring. If friction is present to “damp” its movement, it will come gradually to its new position and stay there, but if the spring is pretty free and has some inertia, it will execute vibrations corresponding to its natural frequency before it comes to rest.

The frequency of the oscillations depends upon the relation of the capacity and the inductance. It can be shown that if the resistance be small, the frequency of the

oscillations is $\frac{1}{2\pi\sqrt{CL}}$, and that there will be no oscillations unless R is less than $\sqrt{\frac{4L}{C}}$, where L is the self-induction in henries, and C is the capacity in farads. It may be remarked here that every circuit has a natural frequency and can be set into a state of oscillation if started off by a series of impulses of that frequency with which it is said to be in **resonance**. In very large alternating current systems, surges of current sometimes of dangerous magnitude can be produced owing to such resonance effects and as will be seen later the resonating property of electric circuits is of great importance in wireless telegraphy.

High Frequency Currents.—The high frequency oscillations obtained by the discharge of condensers through circuits of appreciable self-induction, which may reach frequencies of hundreds of thousands of cycles per second, can be transformed in suitable transformers just as is the case with alternating currents of the low frequencies used in electric light and power or those of somewhat higher frequency used in telephony. Such a transformer is sometimes called a **Tesla coil**. The high frequency currents produced in this way can show some very remarkable effects, which however cannot be entered into here.

CHAPTER XV.

THE ELECTRIC DISCHARGE.

Spark Discharges.—It has been seen that whenever the potential difference between two points separated by air at ordinary atmospheric pressure exceeds that which the dielectric strength of the air can stand, a discharge in the form of a bright spark, making a snapping sound, is produced. Such **sparks** are produced on a small scale when a circuit carrying a current is broken and are increased in intensity when the current is large, and in length when the voltage is high. Minute sparks are produced just before a circuit is closed when the contacts are very near indeed, but have not yet quite touched.

These sparks must not be confused with the arc effects dealt with in Chapter XI. and can occur in circumstances where an arc could not possibly be maintained. The starting of an arc is probably effected in the first instance by the passage of a true spark, which appears to make the air momentarily conducting and thus to enable the arc to follow. The brilliant flashes seen when the current collectors of electric railways or tramways break contact with the live rail or overhead conductor, or when a heavy current is broken by a switch or otherwise, partake chiefly of the nature of very brief arcs.

Switches for electric light and power circuits are often arranged with springs, so that the contacts fly apart when they are opened to prevent the spark being succeeded by a persistent arc which would burn the contacts. In large **quick-break switches**, auxiliary renewable contacts are provided which snap apart after the main current carrying contacts have opened, and take the effect of the spark.

Another method of preventing an arc, called a **magnetic blow-out**, is adopted in tramway controllers and other switchgear. In this case, the circuit opens in a magnetic field which exercises a strong repelling force on the arc and literally blows it out.

True sparks of great power and length can be produced by means of the high voltages obtained from the induction coil and similar apparatus, and from Wimshurst and other electrostatic machines. Speaking generally, the length of spark obtainable increases with the increase of difference of potential, but the shape of the electrodes has some influence on the sparking distance for any particular voltage, and different lengths of spark are obtained if different gases are substituted for air.

Lightning.—The extreme case of the electric spark is the **lightning flash**, and the crash of the **thunder** is merely the equivalent of the snapping noise of an ordinary spark, apparently following the flash, because sound takes longer to reach the observer from the seat of the discharge than light does, and extended to a rolling peal by echoing reverberation from the neighbouring clouds. The huge potentials causing thunderstorms are probably produced by small particles of moisture, each carrying an electric charge, floating in the air being run together into larger particles or drops, and their charges added while their capacities are not greatly increased. The original charges may be due to evaporation or simply to the atmospheric electrification always present in the upper layers of the air.

When we can actually see the flash, in its irregular flickering course, very like that of the course of a spark from a Wimshurst machine (but never doubling back upon itself, like the conventional zig-zag representations of lightning), we call it **forked lightning**, but when the actual flash is hidden from us and we only see the sudden lightning up of the clouds, we call it **sheet lightning**. A lightning discharge, like that of a Leyden jar, is usually oscillatory, and several flashes follow one another over exactly the same course because the first flash makes the air temporarily conducting along its course. This can

be seen in photographs of lightning taken with a moving camera, where the flash appears widened out like a ribbon.

Other Forms of Discharge.—Another form of discharge, sometimes seen from the terminal balls of a Wimshurst or other electrostatic machine when they are very strongly charged and the gap is too great for an ordinary spark to pass, is that called the **brush discharge**. This consists of a diverging brush of pale flickering blue light. If pointed conductors are used, instead of balls, a silent and continuous **glow discharge** can be seen where electrified particles of air are being repelled in the manner referred to on p. 100. The points of light sometimes appearing during thunderstorms on sharply pointed conductors and known as **St. Elmo's fire** are due to the same cause. Partial discharges, of a somewhat similar nature, are visible in the dark from overhead transmission lines worked at pressures of 10,000 volts and over, and are called **corona discharges**.

One property of electric discharges in air, particularly those of the silent variety, is to convert the oxygen of the air into its denser form of **ozone**. The characteristic smell of ozone is often noticed where experiments with high tension apparatus are being carried out; and discharges from flat plates between which a current of air is passed are employed to produce ozone for disinfecting the air in connection with schemes of ventilation, and for other purposes.

Heating effect of Sparks.—A very high temperature is produced within the spark itself which, although only momentary, is sufficient to cause ignition of explosive mixtures of gases. The sparks occurring when a circuit is broken by a switch, circuit breaker, or fuse, the sparks at the brushes of motors, etc., or even the sparks at the contact of electric bells, are sufficient to cause ignition of the explosive gases sometimes present in coal mines, and for this reason all mining electrical apparatus to be safe must be enclosed in flame-tight covers.

Electric ignition has been turned to useful account in gas, oil and petrol engines. In the **high-tension magneto**

system now usually employed, the spark is made by means of a magneto generator, driven by the engine, which supplies current impulses to an induction coil within the apparatus. The primary circuit of the coil is broken at the correct moment by a contact maker, in parallel with a condenser, while the secondary circuit is connected, by a distributor, successively to the insulated terminals of the sparking plugs in the different cylinders in the proper order. Older forms of electric ignition apparatus employed induction coils fed by batteries, and in the so-called **low-tension magneto** system the current from a magneto generator is broken by a mechanical device inside the cylinder.

Effect of Increased Pressure.—If a spark is made to pass between electrodes in compressed air, the same voltage can only produce a spark across a shorter gap than would be required at ordinary pressures, as the dielectric strength of air, and other gases, increases with increase of pressure. For this reason, a sparking plug which has been tested in air and found to give quite a good spark will not necessarily spark under the high compression in the cylinder of the engine.

Effect of Diminished Pressure.—If, on the other hand, the sparks are produced between electrodes in a glass vessel in which the air pressure is gradually reduced, longer and longer sparks are produced by the same voltage ;



FIG. 70.—Discharge under reduced pressure.

and as a vacuum is approached, the character of the discharge becomes completely altered. The compact stream of sparks widens out into a glow which fills a great part of the vessel with a soft light of a bluish or violet colour (Fig. 70), and the discharge passes more easily through the gas, as is shown by the fact that a discharge

will pass with quite a short spark gap in parallel with the tube. Several forms of lamp have been developed in which the glow produced by the electric discharge in rarefied gases is used to provide useful light.

Discharges in a Partial Vacuum.—As the rarefaction of the air or other gas within the tube is increased, the column of light illustrated in Fig. 70, or as it is called, the **positive column**, breaks up into patches called **striae**, and a dark space known as **Faraday's dark space**, separates them from the **negative glow** immediately surrounding the cathode or negative pole. The colour of these luminous effects varies somewhat according to the gas with which the tube was filled before exhaustion began.

A higher degree of exhaustion sends the Faraday dark space F (Fig. 71) further along the tube, and the negative



FIG. 71.—Discharge in partial vacuum.

glow becomes separated from the cathode by another dark space C, known as the **Crookes dark space**, while the positive column is more compressed at the other end of the tube. The conductivity of the gas is now less, and quite a long spark gap must be used in parallel with the tube, to enable a discharge to pass.

Discharges in a High Vacuum.—Carrying the exhaustion to a still higher degree, measurable in millionths of an atmosphere, causes the resistance of the tube to increase to such an extent that a discharge can only pass with difficulty. The Crookes dark space now fills the whole tube, and the only luminous effect is a pale green phosphorescence due to the glass itself, under the influence of the discharge. With the highest degree of vacuum obtainable, no discharge at all will pass.

Cathode Rays.—A number of very remarkable effects are produced in a highly exhausted tube in which the discharge will just pass. Results of experiments show that a species of rays are given out from the cathode, and that it is these rays which, when falling upon the glass, produce the phosphorescence referred to above. This is well shown in an experiment of Crookes in which a mica cross *b* (Fig. 72) is made to cast a shadow on the glass of the tube.

These cathode rays have been the subject of extensive experimental investigations which cannot be entered into

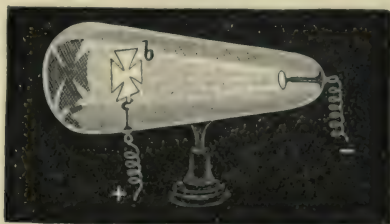


FIG. 72.—Cathode ray tube.

here. They are found to travel normally in straight lines, but to be deflected into curved paths by a magnetic field, to heat objects upon which they fall, and even to exert appreciable mechanical force upon a screen put in their path. They also impart a negative charge to bodies, and cause an improvement of the conducting power of gases through which they have passed. From these and other results, it has been shown that cathode rays really consist of streams of negatively charged particles of definite but minute mass projected from the surface of the cathode at a definite but enormous velocity.

Electrons.—Recent investigations have indicated that these minute particles which are shot off from the cathode in a highly exhausted tube are portions of atoms which detach themselves and each carries the smallest amount of a negative electric charge that can exist. Indeed it is immaterial whether we regard them as particles of matter

carrying a unit electric charge or as constituting the charge itself. A negative charge may be regarded as an excess of these **electrons**, as they are called, and a positive charge as a deficiency of them. It is unfortunate that the names positive and negative had not been chosen the other way round before the electron theory was arrived at. All electric phenomena may be explained by the movement of electrons in some way or other. In a discharge through rarefied gases, they are shot across like bullets from a machine gun, and in a current through a solid conductor, they are passed on from atom to atom just as fire buckets may be passed along a line of men.

Röntgen Rays.—It has been found that when a stream of electrons from the cathode bombards a target or **anti-cathode**, as it is called, within the tube, quite another kind of rays are set up which, unlike cathode rays, penetrate the glass and have certain interesting effects outside the tube. They can, for example, affect a photographic plate in the same manner as ordinary light and can cause certain chemicals to glow with a bright phosphorescence. These rays are called **Röntgen rays** after their discoverer, or sometimes, as he himself named them, X-rays. They are capable of passing through some, but not all, bodies which are opaque to ordinary light.

Most parts of the human body, for example, except the bones, are partially transparent to Röntgen Rays, so that it is possible to obtain a shadow of the hand in which the bones are clearly visible in the semi-transparent flesh. Not only can such a shadow be made to imprint itself on a photographic plate, but it can also be rendered visible by allowing the rays to fall upon a screen covered with a material which glows where the rays fall. Such a screen is called a **fluorescent screen**. In like manner, the position in the body of bullets or other substances, which are opaque to Röntgen rays, can be seen.

It is found that electrons are given off much more freely when the cathode is heated, and one of the most powerful forms of modern Röntgen ray tube employs a cathode of tungsten wire heated by an electric current. Röntgen rays are capable of causing **ionisation** of gases, that is

causing them to become temporarily conducting, but unlike cathode rays are not deflected by a magnetic field. They are now believed to be similar in their nature to light, but to consist of trains of impulses of much higher frequency and less regularity.

Thermionic Valves.—The fact that a stream of electrons is given out by a hot cathode much more readily than a cold one is utilised in the **Fleming oscillation valve** (Fig. 73). In this, the heated filament **F**, usually of tungsten, forms one electrode and the cool plate **P** forms the other in a highly exhausted tube. The apparatus is found to act as a conductor to currents in the direction in which negative electricity (conveyed by the electron stream)

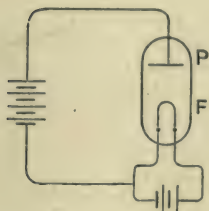


FIG. 73.—Fleming oscillation valve.

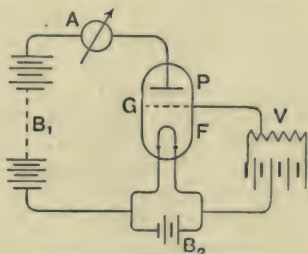


FIG. 74.—Thermionic amplifier.

passes from the hot to the cold electrode, but not in the reverse direction, as an electrode stream cannot be started readily from the cool plate **P**. It thus acts as an electric non-return valve or **rectifier**, and if included in an oscillatory circuit, only allows the half-waves in one direction to pass. Such tubes are called generally **Thermionic valves** and the two electrode form just described is sometimes called a **diode**.

Some interesting effects are produced in the **triode** or three-electrode form of thermionic valve represented in Fig. 74. In these, the third electrode takes the form of a grid of wire, **G**, interposed between the filament and the plate. Suppose a high voltage battery **B₁** be connected between **P** and **F**, independent of the small battery **B₂**

supplying the current to keep the filament hot. This battery will keep up the stream of electrons freed by the hot cathode through the grid to the plate and will pass a certain **plate current** which can be measured by the galvanometer. Now suppose that a variable E.M.F. be applied to what we will call the **grid circuit**, so that the grid can be made positive or negative relatively to the filament. If the grid is negative, the electrons trying to pass will experience a repelling force tending to drive them back and the plate current will be greatly diminished or will even be stopped. A very small positive charge on the grid, on the other hand, will encourage and increase the flow of electrons, and the plate current will be much increased.

The apparatus can thus be used as an amplifier of very small changes of current in the grid circuit as they reappear as very large changes in the plate current. The thermionic **amplifier** is not only extraordinarily sensitive to very small variations, but can deal with those of very high frequency without causing distortion, and is thus capable of being employed on telephone circuits as the equivalent of a relay to avoid some of the difficulties arising in connection with long lines which were hinted at in Chapter XII. It has also several very important applications in wireless telegraphy.

CHAPTER XVI.

ELECTRIC WAVES AND WIRELESS TELEGRAPHY.

Electric Waves.—In dealing with the oscillatory discharge of a condenser, the surging backwards and forwards of the charge was considered, but no mention was made of the effect on the electric field, in the surrounding medium, of the rapid changes of potential produced. Soon after the oscillatory nature of the discharge was known, Clerk Maxwell, while investigating the matter mathematically, arrived at the conclusion that the electric disturbance produced must travel outwards into space at a very high velocity in the form of **electric waves**, in just the same way that ever-widening circles of ripples are produced, when the still surface of a pond is disturbed by a stone dropped into it. He further calculated that the velocity of these waves is the same as that of light (3×10^{10} cm. per sec.), and arrived at the theory that light itself is nothing more or less than electric waves of this kind, but of much higher frequency and consequently smaller wave-length.

The existence of these electric waves was afterwards demonstrated experimentally by Hertz, Lodge and others; and their properties were seen to be very similar to those of light, with the great difference that their wave-lengths varied from a few millimetres to a few thousand metres, whereas those of light range from four to eight thousandths of a millimetre.

Wireless Telegraphy.—These electric waves are the basis of modern **wireless telegraphy**. At the sending station, a circuit possessing suitable relations of inductance and capacity, usually including a spread of wires mounted on

tall masts and connected to the earth, is put into a state of electrical oscillation by one of the methods outlined below, and is thus caused to radiate electric waves with a wavelength of anything from a few hundred feet to 4 or 5 miles. At the receiving station, a similar circuit is provided, capable of oscillating at the same frequency as that of the sending station. The waves falling upon this circuit cause minute surgings of electricity to take place in it, which are detected by one of the methods referred to below. The trains of waves are broken up into the dots and dashes of the Morse code as in ordinary telegraphy. It is not possible here to do more than outline a few of the main principles upon which the leading methods depend.

The Spark Method of Producing Electric Waves.—A simple arrangement for producing electric waves for wireless telegraphy is shown diagrammatically in Fig. 75.

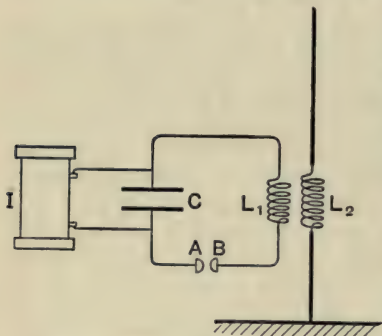


FIG. 75—Wireless transmitting circuit.

The high voltage impulses from the induction coil I raise the potential of the condenser C till it sparks across the gap AB, causing oscillations in the circuit C, A, B, L_1 . The aerial is inductively coupled to the first oscillating circuit by an oscillation transformer L_1L_2 , or **jigger** as it is sometimes called, through which the oscillations are communi-

cated to it, causing surgings of potential up and down the aerial, and in and out of the earth. These produce the waves which are radiated into space, to be picked up by any station having suitably adjusted apparatus.

Generally speaking, the waves radiate equally in all directions, but certain shaped aerials can make the waves in one particular direction stronger than in others, and thus give a certain amount of **directive** effect. The aerial

circuit is designed and adjusted to have the same frequency of oscillation as that of the first oscillating circuit. Such a spark method does not give out a continuous series of waves, but produces short trains of rapidly diminishing waves corresponding to each spark, somewhat as represented in Fig. 76. Many different forms of spark

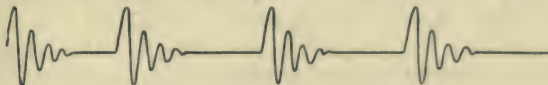


FIG. 76.—Trains of waves from spark installation.

gap have been employed, in some of which special arrangements are adopted to prevent the air remaining conducting (or ionised) after the first spark has passed, because for certain reasons it is best to excite the oscillations in the aerial circuit by a few powerful swings in the spark circuit.

Continuous Waves.—In other systems, **continuous waves** as represented in Fig. 77 are produced. One method is

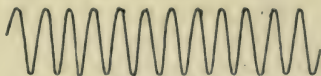


FIG. 77.—Continuous waves.

to employ a **high frequency alternator**; that is to say an alternator giving a sufficiently high frequency to throw the aerial circuit into oscillation without any spark discharge at all. By surmounting considerable mechanical and electrical difficulties such alternators have been made for frequencies of 20,000 cycles per second or more, and are in use in several large stations.

In the **arc system**, originated by Poulsen, advantage is taken of the fact (first discovered by Duddell) that, owing to certain relations between the current in an arc and the voltage across it, whereby a small change of current corresponds to a large change of voltage, a condition of instability is produced when an oscillating circuit is connected in parallel with the arc. By this means oscillations are maintained continuously in the oscillating circuit, which

can therefore be made to cause the radiation of continuous waves. A number of special conditions are required for the best results, but the difficulties have been largely surmounted and arcs consuming hundreds of kilowatts are in use in some of the more powerful stations.

Mercury vapour arcs can be made to produce oscillations in a somewhat similar way, but the most promising generator of electric waves is the thermionic valve described in the last chapter. This also has the requisite relations between current and voltage to produce the necessary instability when associated with an oscillating circuit. In this case the oscillations are taken from the grid circuit. Very much less power is required for producing waves by this method than by any other.

Reception of Electric Waves.—It will be realised that the voltage surges induced in the receiving aerial are exceedingly minute, and apparatus of a special nature and of great sensitiveness is required for their detection. The oldest detector is that known as the **coherer**. This consists of a tube containing metal filings, between suitable electrodes, connected in the receiving aerial circuit. As soon as the received oscillations pass through it, its resistance becomes very markedly lowered and a current will pass in a local circuit, where one would scarcely pass before. The apparatus can thus be used as the equivalent of a relay, but requires an automatic arrangement to restore it into its practically non-conducting state by tapping after every signal has passed. The coherer can be made to work almost any kind of telegraph receiving instrument, but is far eclipsed in sensitiveness and reliability by the later detectors.

Another detector considerably used at one time depended upon the power of electric oscillations of effecting change of magnetisation in a magnetised iron wire. This wire travels along and acts inductively on a telephone circuit, so that the passage of a succession of unmagnetised patches produces a recognisable sound in the telephone.

In the **crystal detector**, the point of a crystal of a particular material bears against a metal surface forming a contact which is found to have the peculiar property of

acting as a rectifier, that is of allowing currents to pass in only one direction. If such a rectifier be placed in series with an ordinary telephone receiver, which without it would not be able to respond to the high frequency of the waves, it allows impulses in one direction only to pass with the result that all those in each group add together their effects in pulling the diaphragm of the telephone which is released again in the interval between the trains of waves. A sound is therefore heard in the telephone corresponding to the frequency of the spark, which is well within the limits of the ear. The connections of a crystal detector circuit are shown in Fig. 78. In another form of rectifier, known as the **electrolytic detector**, a fine platinum wire dips into a cup of dilute sulphuric acid and a polarising effect is produced.

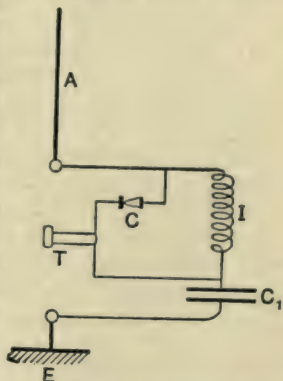


FIG. 78.—Crystal detector circuit.

An even better rectifier for the purpose is the **thermionic valve**, the rectifying properties of which were referred to in the last chapter. The rectified impulses can be considerably magnified by further thermionic valves acting as amplifiers in the way also indicated in Chapter XV., and indeed the sensitiveness may be multiplied to almost any extent by using rows of several of these amplifying valves arranged in **cascade**, that is, so that each amplifies the effect of the last. It will be seen that the thermionic valve plays three separate roles in wireless telegraphy, for it is employed as an oscillator, as a receiver, and as an amplifier.

In order to receive continuous waves, certain modifications in the arrangements have to be made. Even with a rectifier, a telephone is of no use unless the waves are broken up into trains of audible frequency, or at any rate are given variations of such a frequency.

This result can be secured mechanically by an intermittent contact maker (called a **ticker**), producing a result something like Fig. 79, or electrically by superposing

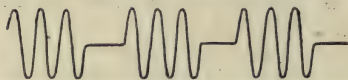


FIG. 79.—Continuous waves broken up by ticker.

another wave-length upon the received waves by means of a separate source of oscillations and as another valve tube connected to a suitable oscillating circuit. This, by adding to the effect when the main and auxiliary oscillations are quite or nearly in phase and diminishing the resultant effect when they are quite or nearly in opposition, will cause periodic variations on the principle of interference known in the theory of sound as **beats**, giving a result somewhat as shown in Fig. 80. The note heard in

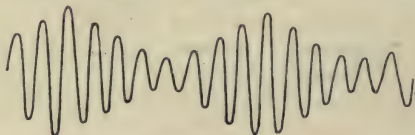


FIG. 80.—Waves for "beat" reception.

the telephone will then be that corresponding to the beat frequency. This method is known as **heterodyne** reception.

Syntony.—From what has been said, it is clear that a receiving circuit with suitably proportioned self-induction and capacity can respond with much more power to one particular wave-length of frequency than to any other. Adjustment of the self-induction and capacity of circuits to suit a particular wave-length is spoken of as **tuning** the circuit, and two circuits tuned so that they resonate to the same wave-length are said to be in **syntony** with one another. It is possible to arrange circuits so that they are either very sharply tuned and scarcely respond at all except to their own wave-length, or to make them less sensitive but able to respond to a wider range of wave-lengths. Sharp tuning is of advantage when it is desired

to pick up signals from one particular station when several others of different wave-lengths are working at the same time.

A certain amount of stray waves due to atmospheric electricity are often present, and interference from these is much less with sharply tuned than with loosely tuned circuits. The degree of completeness with which the lines of force due to the primary of the oscillation transformer interlace the secondary, or as it is called the *tightness* or looseness of the coupling, has much to do with the sharpness of the tuning obtainable.

Wireless Telephony.—If the variation of the strength of the continuous oscillations be effected by including a microphone transmitter in some part of the sending circuit, then the wave trains will vary in sympathy with the sounds spoken into the transmitter, just as the line current does in the ordinary telephone, and the receiving apparatus, without any modification whatever, will pick up and respond to these variations, and the sounds will be reproduced in the receiving transmitter. This is the basis of **wireless telephony**, which in principle is as simple as wireless telegraphy, although much more delicate apparatus is required. For long-distance speaking, wireless telephony has advantages over line telephony in that the distortion effects already referred to are entirely avoided.

The whole subject of wireless telegraphy, and more particularly wireless telephony, is one of fascinating interest and involves many considerations that there is no space to touch upon here. Like many developments in the applications of electricity, it originated from the study of electrical theory for its own sake, while the investigations which have been undertaken in the pursuit of its application to the use and convenience of man have in their turn led to further discoveries and the more complete elucidation of the theories from which it originally sprang.

EXERCISES.

CHAPTER I.

1. A battery of two cells in series, each with an E.M.F. of 1.07 volts and an internal resistance of 2 ohms, is connected to a circuit with an external resistance of 10 ohms. What will be the current in the circuit and the drop of potential across the terminals when the current is passing ?

2. Two lamps have respectively resistances when alight of 400 ohms and 800 ohms. They are both designed to light up when $\frac{1}{4}$ of an ampere is passing. For what voltages are they suitable ?

3. A battery of 2 cells, each of an E.M.F. of 2 volts, is connected to a circuit, and a current of 0.01 ampere flows. What is the resistance of the whole circuit ?

4. Ten amperes are flowing along a uniform wire with a resistance of 0.45 ohm per foot. What will be the Potential Drop between two points on the wire 9 inches apart ?

5. What is the combined resistance of 15 lamps each of 50 ohms resistance arranged respectively (a) all in parallel, (b) all in series, (c) in 5 parallel groups of 3 in series, and (d) in 3 parallel groups of 5 in series ?

6. What voltage must be applied in each of the cases in the last example for a current of half an ampere to pass through each lamp, and what will be the total current going into and out of the group ?

CHAPTER II.

7. Find the resistance at 0° C. and at 20° C. of a mile of hard drawn copper wire 0.25 in. diameter.

8. A coil of copper wire is found to have increased its resistance from 100 ohms to 106 ohms. How much has its temperature risen?

9. What current is taken by a 30 watt-lamp on a 200 volt circuit? How long will it have to burn to consume one Board of Trade Unit?

10. A coil of wire with a resistance of 20 ohms is heated by a current of 2.5 amperes. How many calories of heat will be developed in one minute, and supposing that all the heat is absorbed by 50 c.c. of water, by how much will the temperature of the water rise?

11. A radiator on a 200 volt circuit takes 7.5 amperes. How much will it cost to run per hour with electricity at 3d. per unit?

12. Assuming no loss of heat, how many watts will be required to bring 1 litre (1000 c.c.) of water from 59° F. (15° C.) to boiling point (100° C.) in fifteen minutes?

CHAPTER IV.

13. What magnetising force will be produced by a current of 2 amperes in a solenoid 30 cm. long, consisting of 150 turns?

14. What induction will be produced in a piece of iron in the above solenoid if the permeability has a value of 1200?

15. A piece of iron subjected to a magnetising force $H = 7$ is found to have produced in it an induction $B = 12,000$. What is (a) its permeability, (b) its intensity of magnetisation, and (c) its susceptibility?

CHAPTER V.

16. Two equal poles repel each other with a force of 25 dynes, when placed 5 cm. apart. What is their pole strength?

17. What is the magnetic moment of a compass needle 2 cm. long, with a pole strength of 4 units?

18. What is the couple tending to deflect the needle in the last exercise when it is placed at right angles to the earth's field (assume $H = 0.18$)?

CHAPTER VI.

19. What will be the field at the centre of a coil of 25 turns of 25 cm. radius, carrying $7\frac{1}{2}$ amperes, and what force will be exerted on a pole of strength 5 units?

20. Two parallel wires carry 50 and 100 amperes, and are 10 cm. apart. What is the force between 20 cm. length of them?

21. A motor gives out 20 H.P. when taking 42.5 amperes on a 440 volt circuit, what is its efficiency?

22. A motor, the efficiency of which may be taken as 85 per cent., is required to give 40 H.P. for 6 hours. What will be the cost of running with electric supply at 2d. per unit?

CHAPTER VII.

23. The cathode of a silver voltameter weighs 5.263 grammes before and 5.374 grammes after a current has been passing through the apparatus for 5 minutes. What has been the average current passing during this time?

24. In an electrolytic plant for the manufacture of hydrogen in which there are no two cells in series, what current will be required to give an output of 1000 cubic metres of hydrogen per hour (assuming that one litre (1000 c.c.) of hydrogen weighs 0.09 grammes)?

CHAPTER VIII.

25. A wire 10 centimetres long moves with a velocity of 40 cm. per second across a field of 10,000 lines per square centimetre. What E.M.F. will be produced in it?

26. A dynamo is required to light 300 lamps, each taking $\frac{1}{3}$ ampere at 100 volts. Assuming the efficiency to be 85 per cent., what horse-power will be necessary to drive it?

CHAPTER IX.

27. At what speed will a twelve pole alternator give a frequency of 60 cycles per second?

28. If the same alternator has a true sine wave form, and gives a maximum voltage of 311 volts, what is its virtual voltage?

29. What current will be given by the same machine if the total self-induction of the circuit be 0.05 henry, and the total resistance, 20 ohms ?

30. In the above example what will be the power factor of the circuit ?

CHAPTER X.

31. The moving coil of an ammeter requires a potential difference of 0.15 volt to give a full deflection. What should be the resistance of a shunt to be used up to 1000 amperes ? (The effect of the resistance of the moving coil itself may be neglected.)

32. A Wheatstone's bridge arranged as in Fig. 51, has resistances of 10 and 1000 ohms in the arms AC and AD respectively, and a balance is attained when plugs are withdrawn from resistance coils totalling 147 ohms. What is the resistance in the arm CB ?

CHAPTER XIV.

33. A plate condenser with the plates 2 mm. apart is found to have a capacity of 0.001 mf. What will be the capacity if a sheet of glass with a specific inductive capacity of 2.5 times that of air and 1.5 mm. thick be inserted, and the plates brought together to touch it on both sides ?

34. A set of three condensers of capacities 1, 0.5 and 0.25 mf. respectively are connected, (a) in series, and (b) in parallel. What is the resultant capacity in each case ?

35. What current will an E.M.F. of 100 volts at 50 cycles produce in a circuit of 10 ohms resistance, a self-induction of 0.5 henry and a capacity of 25 mf. ?

36. What is the frequency of oscillation of the discharge of a condenser of 0.05 mf. capacity through a circuit of negligible resistance with a self-induction of 0.00005 henry ?

EXPERIMENTS.

CHAPTER I.

1. Obtain a pocket-lamp and remove the battery and the lamp bulb from it ; fix wires to the terminals of the battery. Include the lamp bulb in the circuit and complete the circuit with various materials by touching the wires on them. If they are conductors, the lamp will light up ; if they are insulators it will not. Do not on any account take the circuit direct from the battery without including the lamp, as the lamp is wanted to indicate when the current is flowing, and without it the battery would be damaged by taking too much current from it.

Wrap one wire round the metal screw collar of the lamp and touching the loose end of the other to the material



FIG. 81.

to be tested. The centre contact of the lamp can then be touched upon another point on the material, when it will be seen whether the lamp lights up or not (Fig. 81).

2. Obtain two pocket-lamp batteries of the ordinary size which have two cells in series, and several spare $2\frac{1}{2}$ volt lamp bulbs. Get also some copper wire and some thin iron wire, which has a much higher resistance than copper. Try all sorts of circuits to get an idea of how changes in E.M.F. and resistance affect the current.

Arrange two lamps in series and see that one battery will not light them up properly, but that two batteries in series will.

Now put the lamps in parallel, one battery will now light them (although the current is rather more than is

good for the battery to stand for long). Include some of the thin iron wire in the circuit, and by means of a sliding contact see how including more or less resistance in the

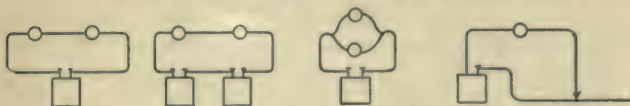


FIG. 82.

circuit alters the current and therefore the brightness of the lamp. These arrangements are shown diagrammatically in Fig. 82.

A convenient rheostat for simple experiments can be made up by fixing a length of iron wire in a zig-zag way to



FIG. 83.

battens on a board as in Fig. 83, and taking the current off from any point of the wire by a spring clip.

3. Make up any number of other arrangements for yourself. Think out what the effect ought to be and see if you are right, but take care not to have a resistance much lower than that of the lamp in the circuit, or an extreme current will be taken out of the battery and it will be spoilt.

CHAPTER II.

4. Make up a circuit consisting of a battery and a lamp and iron wire, arranging the length of the wire so that, with two batteries in series, the lamp will light up comfortably; that is to say with the resistance of the wire about the same as that of the lamp when hot. When you have determined how much wire is required, coil it up into as compact a little coil as you can without the turns touching each other. Heat this little coil of iron wire in the flame of a spirit lamp, or gas burner, while the lamp is alight, and notice how the increase in its resistance cuts down the current and causes the lamp to glow less brightly.

Incidentally, not only is the effect of heat upon the resistance of the iron wire seen, but also the effect of the current in producing heat in the lamp and the way in which the heat

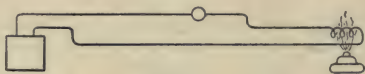


FIG. 84.

produced depends on the strength of the current. A convenient way of arranging the apparatus is shown in Fig. 84.

CHAPTER III.

5. Make up a coil, or solenoid, by fitting wooden ends to a cardboard or glass tube and winding several layers of cotton-covered copper wire upon it. Obtain a rod of soft iron that will fit inside so that it can be drawn out without difficulty, and long enough for the ends to project an inch or so. An ordinary small pocket compass will also be required. Arrange a circuit so that a fairly strong current can be passed through the coil, and include a switch so that it can be put on and off as required.

The little pocket-lamp battery which we have been using will hardly be powerful enough. Either use "dry cells" of larger size, or an accumulator such as is used for ignition and lighting on motor cars. A resistance may be required in series with the solenoid to keep the current within safe limits.

Put the current on and the iron bar will become a magnet. Notice how it will attract and hold on to all sorts of iron things, but will not pick up anything of brass or other non-magnetic material, and that everything falls off when the current is switched off.

6. Trace carefully which way round the current is going at each end (if you know which is the positive pole of the battery) and bring up the compass near each pole in turn, noticing that the "counter-clockwise" end attracts the south-seeking pole of the needle, and is therefore itself a North Pole and *vice versa*.

7. Take the iron core out and put it in the other way round and see that it makes no difference. Then undo the wires and connect them up the other way round and see that the poles have changed round.

8. Finally take out the iron altogether and see that the solenoid still attracts the needle although not so strongly. Move the compass about and endeavour to trace out the course of the lines of force.

9. Make a circular flat coil about 4 ins. in diameter of a dozen turns or so of cotton-covered wire and mount the compass in the centre on a little stand (an empty cotton reel is about the right size). This forms an elementary tangent galvanometer. Turn it round until the coil lies parallel to the needle and pass a current through it from your dry cells in series with a lamp. Check what the deflection is in the direction given by the "Snow" rule, if you know which is the positive pole of the battery. Or, if you do not, find out which it is by this rule and mark it. Put your rheostat into the circuit and see the deflection rise and fall as you vary the current; reverse the current by changing the wires over, and see that the deflection is in the opposite direction.

CHAPTER IV.

10. If possible construct a small Ewing model. Unless a number of little compass needles similar to those in watch chain charm compasses can be procured, or needles made from elongated diamond-shaped pieces of steel with a centre punch mark for the pivot, needles can be made from the

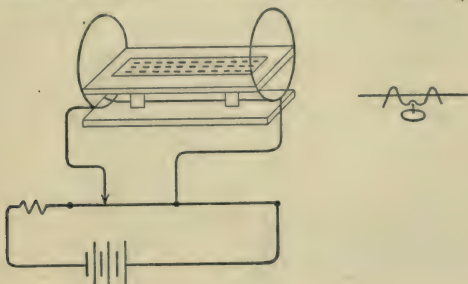


FIG. 85.

halves of darning needles pushed through holes in a narrow strip of brass bent as shown at *A* in Fig. 85. These can be pivoted on the upturned points of drawing pins stuck in regular rows on a card, or better, on a sheet of glass.

The field is most conveniently produced by two coils, one at each end of a little table on which the group of magnets can rest. By gradually increasing and diminishing the current all the phenomena described on pages 25-27 can be studied. A convenient way of steadily increasing the current, first in one direction and then in the other, is by means of a slide-wire resistance as shown in Fig. 85. One lead to the coil is taken from the middle point of the wire and the other is connected to the sliding contact, which at the start of the experiment is put at the centre so that although there is a current in the slide wire, there is no P.D. applied to the coils. Moving the contact to the right and back will give a current "wave" in one direction and moving it to the left will give the wave in the other direction required to complete the cycle. A little experimenting will be necessary before suitable proportions for the wire are found.

11. With this apparatus try to map out the field produced by the coils, using a single compass needle. Find out the direction of the line of force by sprinkling iron filings evenly on a glass plate on the table and watching them arrange themselves in little ridges along the lines when the current is put on.

Rather instructive results can be obtained also by putting flat pieces of iron of various shapes under the glass and seeing how they affect the course of the lines.

12. The magnetic properties of nickel are more affected by temperature than are those of iron, and are lost entirely

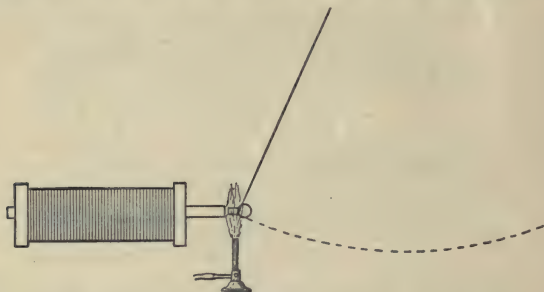


FIG. 86.

at quite a moderate temperature. A pretty way of showing this is to make a long pendulum (from the ceiling of a high

room if possible) with a piece of nickel attached to the bob. At one end of its swing it is arranged to touch the pole of an electromagnet to which it is held. A gas flame is arranged to heat the nickel, and it soon reaches a temperature where the nickel is non-magnetic and falls away from the magnet. During the swing of the pendulum the nickel cools sufficiently to become magnetic again, and when it is back close to the electromagnet, it is attracted and held on only to be heated again and to fall away as before. This action can be kept going indefinitely (Fig. 86).

CHAPTER V.

13. With a horseshoe, or bar, magnet and a compass needle, examine the leading effects of magnets.

See that the magnet picks up magnetic, but not non-magnetic, material by placing it in a box of mixed iron and brass nails and screws, etc.

14. Small magnets can be made from sewing needles by stroking the needles from end to end in one direction with one pole of an ordinary magnet. Test their polarity by floating them on a cork and seeing which end points to the north or by bringing them near a compass needle and noting which end is attracted and which is repelled. Break a magnetised needle in two and see what becomes of the poles.

15. The distribution of the field produced by a magnet can be seen with the help of iron filings. Make up various combinations of magnets and pieces of iron and see the results when iron filings are sprinkled on a piece of paper or glass over them.

Note.—It is often asked why magnets are usually recommended to be kept with a piece of iron called a *keeper* across the poles. The effect of this is to provide a path for the lines of force so that they do not leave the iron. Thus the effect of the poles which have a demagnetising influence on the magnet is avoided.

CHAPTER VI.

16. Make up from some springy wire, a loosely coiled helical spring; fix one end to a stand and let the other dip into a small vessel containing mercury. Pass a fairly strong current through the spring from a battery in series

with a suitable resistance, or other source of supply, and see the spring contract and lift itself out of the mercury (Fig. 87). The point of the spring and the leading in wire to the mercury bath should be cleaned with acid and amalgamated

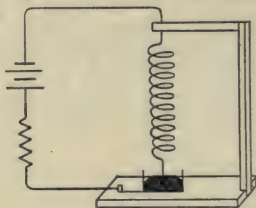


FIG. 87.

with mercury to ensure a good contact being made. (This is a very old experiment originally devised by the author's grandfather and known in the older text-books as "Roget's dancing spiral.")

CHAPTER VII.

17. Make up a simple primary cell by immersing a piece of zinc and a piece of copper in a jar containing salt and water. Bring wires from each plate to the rough galvanometer made in Experiment 9, and see by the deflection of the needle that a current is passing. Check its direction by the "Snow" rule, and reverse the wire to see that the deflection is then in the opposite direction. Leave the current on for a little while and see the deflection diminish as the cell becomes polarised. Small bubbles of gas (hydrogen) will be seen on the surface of the copper. Try various combinations of metals; a half crown and a penny, for example, and see which is the positive and which the negative. Also try two plates of the same material and see if any deflection is produced.

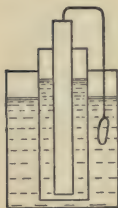


FIG. 88.

18. Make a wax impression of a medal or other object; brush it over with blacklead to give it a conducting surface, and attach it to a wire, taking care that the wire makes contact with the blacklead surface. Get a porous pot, fill it with salt and water, and stand it in a jar of copper sulphate dissolved in water. Attach the end of the wire

carrying the mould to a piece of zinc, place the zinc in the porous pot, and the mould in the copper sulphate as in Fig. 88. The arrangement forms a combined battery and electrolytic cell. A current will flow through the wire and will deposit copper upon the mould. Allow this to go on until a thick coating of copper is produced, when the mould can be lifted out and the wax removed, leaving an electrotype or copper reproduction of the medal.

CHAPTER VIII.

19. The original experiment of inducing currents by inserting a bar magnet into and withdrawing it from a solenoid can be performed if the solenoid has a good many turns and the galvanometer is fairly sensitive.

20. By adding a secondary winding over that of the coil used in the experiments on Chap. III. and connecting it to a galvanometer, the momentary currents induced when the current in the primary is made or broken can be clearly detected.

Another way is to make a little coil of a good many turns which will just pass over the projecting pole of the electromagnet made in Experiment 5, and slip it off and on suddenly while it is connected by flexible wires to a galvanometer.

CHAPTER XIII.

21. A simple gold-leaf electroscope, as represented in Fig. 89, can be made, without much difficulty, using either "Dutch metal" or real gold-leaf attached by gum or otherwise to the lower end of a stout wire passing through the cork of a glass jar and soldered to a penny, or other metal disc, at the upper end. The insulation will be much improved if the wire passes through a glass tube coated inside and out with shellac varnish.

Rub a stick of sealing wax upon a piece of flannel, or fur, and see that it is electrified, first by its power of attracting light objects, and then by presenting it to the disc of the electroscope when the leaves will be seen to diverge. Remove the rod and they will resume their drooping position.



FIG. 89.

Present the electrified rod again, and while it is near the electroscope, touch the disc with the finger. The leaves will collapse, but will open out again when the rod is removed. The electroscope will then be positively charged. If a positively charged body be brought near it, the leaves will diverge still more, but the approach of a negatively charged body will cause them to collapse unless it is brought very near, when, if the charge is strong, the leaves may open out again owing to the potential of the disc becoming temporarily negative.

Try a number of materials and determine in this way whether their charges are positive or negative and reverse the action by first charging the electroscope with a negative charge. Notice also that in either case the leaves have their divergence reduced by the presence of an earthed conductor such as the hand, as the potential of the disc is thereby brought nearer to that of the earth.

ANSWERS TO EXERCISES.

1. 0.153 amperes, 1.53 volts. 2. 100 volts, 200 volts.
3. 400 ohms. 4. 3.375 volts.
5. (a) 3.33 ohms. (b) 750 ohms. (c) 30 ohms. (d) 83.3 ohms.
6. (a) 25 volts. (b) 375 volts. (c) 75 volts. (d) 125 volts.
(a) 7.5 amp. (b) 0.5 amp. (c) 2.5 amp. (d) 1.5 amp.
7. 0.824 ohms, 0.895 ohms. 8. 13.95 deg. C. or 25.1 deg. F.
9. 0.15 amperes, $33\frac{1}{3}$ hours. 10. 1800 calories, 36 deg. C.
11. $4\frac{1}{2}$ d. 12. 393 watts. 13. $H = 12.57$.
14. $B = 15,100$ (approx.). 15. (a) 1714. (b) 955. (c) 136.4.
16. 25 units. 17. 8 units.
18. 1.44 dyne-centimetres. 19. $H = 4.7, 23.4$ dynes.
20. 10 dynes. 21. 80 per cent. 22. 35s.
23. 0.302 ampere. 24. 240 amperes. 25. 0.04 volts.
26. 23.6 Horse-power. 27. 600 R.P.M. 28. 220 volts.
29. 8 amperes. 30. 0.73. 31. 0.00015 ohm.
32. 14.7 ohms. 33. 0.033 microfarad.
34. (a) 1.75 mf. (b) $\frac{1}{4}$ mf. 35. 3.47 amperes.
36. 100,000 cycles per sec. (approx.).

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